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# BERTHA — A Versatile Transmission Line and Circuit Code


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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An improved version of the NRL transmission line code of W.H. Lupton is presented. The capabilities of the original program have been extended to allow magnetically insulated transmission lines, plasma opening switches, imploding plasma loads and discrete element electrical networks, for example, to be modeled. BERTHA can be used to simulate any system that can be represented by a configuration of transmission line elements. The electrical behavior of the system is calculated by repeatedly summing the reflected and transmitted waves at the ends of each element. This program is versatile, easy to use and easily implemented on desktop microcomputers.

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CONTENTS

# BERTHA — A VERSATILE TRANSMISSION LINE AND CIRCUIT CODE

## INTRODUCTION

Transmission line codes have many applications ranging from the simulation of pulsed power devices to the solution of problems involving electrical networks. BERTHA is an improved version of the elegant code of W.H. Lupton,[1] which has been in use at the Naval Research Laboratory and elsewhere for many years. The capabilities of the original code have been extended and the general format has been changed to yield greater versatility.

This program is capable of simulating any system that can be represented by a configuration of transmission line elements, including pulsed power generators, magnetically insulated transmission lines,[2] discrete element electrical networks and their mechanical, thermal and fluid analogs. The program can handle any numbers (limited only by memory) of line elements (with arbitrary initial voltages and/or currents and optional shunt and series resistances), series and parallel tees, self-break and command triggered switches and reactive components. Arbitrary loads, which may depend on time as well as various electrical quantities (e.g., a Child-Langmuir electron beam diode with gap closure) may be included, as may variable impedance line elements. An example of the latter is an imploding plasma load[3] which may be represented by an inductance that increases with time. In addition, external waveforms may be fed into the configuration.

Of particular note is the fact that this program was written with the now ubiquitous desktop microcomputer in mind. The program described here was written in BASIC for the Tektronix 4050 series microcomputers. Of course, increases in permissible configuration size and speed of execution will result when the code is placed on a larger machine.

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## BACKGROUND

A transmission line supports waves of voltage and current propagating in two directions and the sum of these two traveling waves determines the standing wave voltage and current which are physically measured. As the current and voltage of a single traveling wave are related by the characteristic impedance of the line, all relevant electrical quantities may be expressed in terms of the two traveling wave voltages. The instantaneous standing wave voltage, V, and current, I, at a given location are given by (see Fig. 1):

$$V = V_1 + V_2$$

$$I = (V_1 - V_2)/Z_o$$

where $V_1$ and $V_2$ are the voltages of the waves traveling out of and into the line, respectively, and $Z_o$ is the line impedance. Likewise, the power flow, P, out of the line is given by:

$$P = IV = (V_1^2 - V_2^2)/Z_o \quad .$$

A wave incident on an impedance discontinuity will be split into reflected and transmitted waves according to:

$$r = \frac{Z_1 - Z_o}{Z_1 + Z_o}$$

$$t = \frac{2Z_1}{Z_1 + Z_o}$$

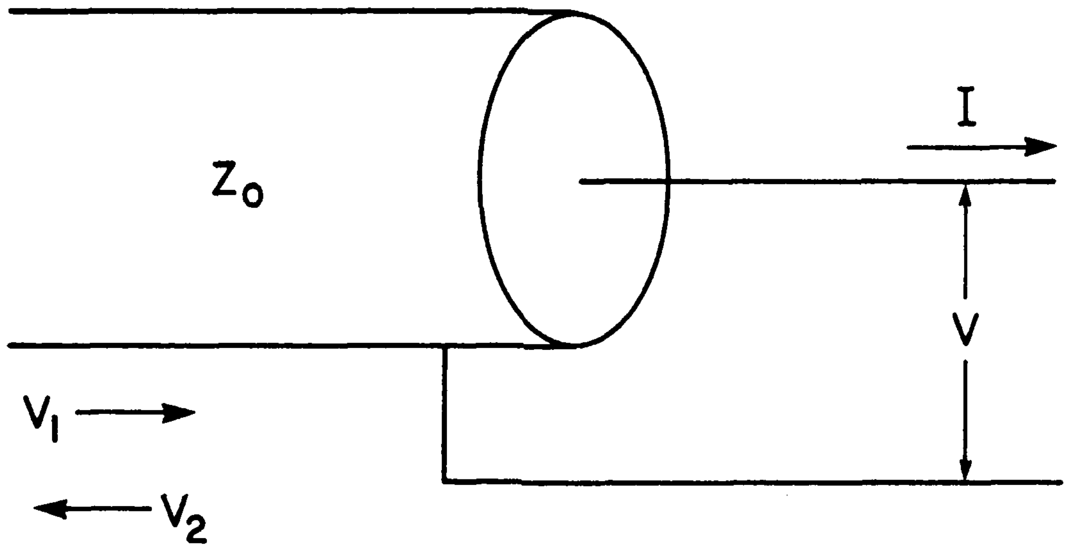



Fig. 1: Definition of the two traveling voltage waves.

where $Z_o$ is the line impedance, $Z_l$ is the load impedance and r and t are the reflection and transmission coefficients for the traveling wave voltage. These may easily be extended to describe more complex junctions and the reflection and transmission coefficients for the junctions used in this program are given in Appendix A.

The case of a reactive load would appear more cumbersome to treat since the reflection from a reactive load depends, in a somewhat complicated manner, on the time rate of change of the incident pulse. However, the problem can be simplified by noting that an inductor, for example, is actually a very short high impedance transmission line element. The line element impedance, Z, is related to the total lumped inductance, L, by

$$L = Z\tau$$

where $\tau$ is the one-way transit time. Likewise, a capacitor is a short, low impedance line element, with the lumped capacitance, C, given by:

$$C = \tau/Z \quad .$$

The representation of reactive components by short line elements in effect replaces the differential equations involved with finite difference equations and the operations of integration and differentiation are replaced by simple arithmetic operations.

In fact, entire networks of passive lumped parameter elements may be represented by transmission line element configurations by using the equivalences shown in Fig. 2-a. For example, the simple RLC circuit of Fig. 2-b may be modeled by the configuration shown in Fig. 2-c.

This code may also be used to model the many analogs to transmission lines and electrical networks. For instance, multi-layer thin films may be simulated by strings of transmission line elements, with the indices of refraction being represented by the line element impedances.[4] In general, then, a large number of physical systems can be modeled by configurations of transmission line elements and resistors. To predict the behavior of these systems it is only necessary to account for the waves running around the configuration.

## DESCRIPTION OF PROGRAM

Rather than following particular waves around the circuit, the program keeps track of the instantaneous values of the two traveling (voltage) waves at the two ends of each line element: the wave, V1, that is incident on the junction from within the element, and the wave, V2, that is leaving the junction and traveling into the element. V2 is made up of the reflected portion of V1 from the same line element and the transmitted portions of V1's from the other line elements connected to the junction. For a configuration comprised of N elements there are thus 4N quantities which must be recalculated at each timestep. There are N pairs of equations describing the transit of waves within line elements: the incident wave at an element end is the wave that left the opposite end of that same line element at the

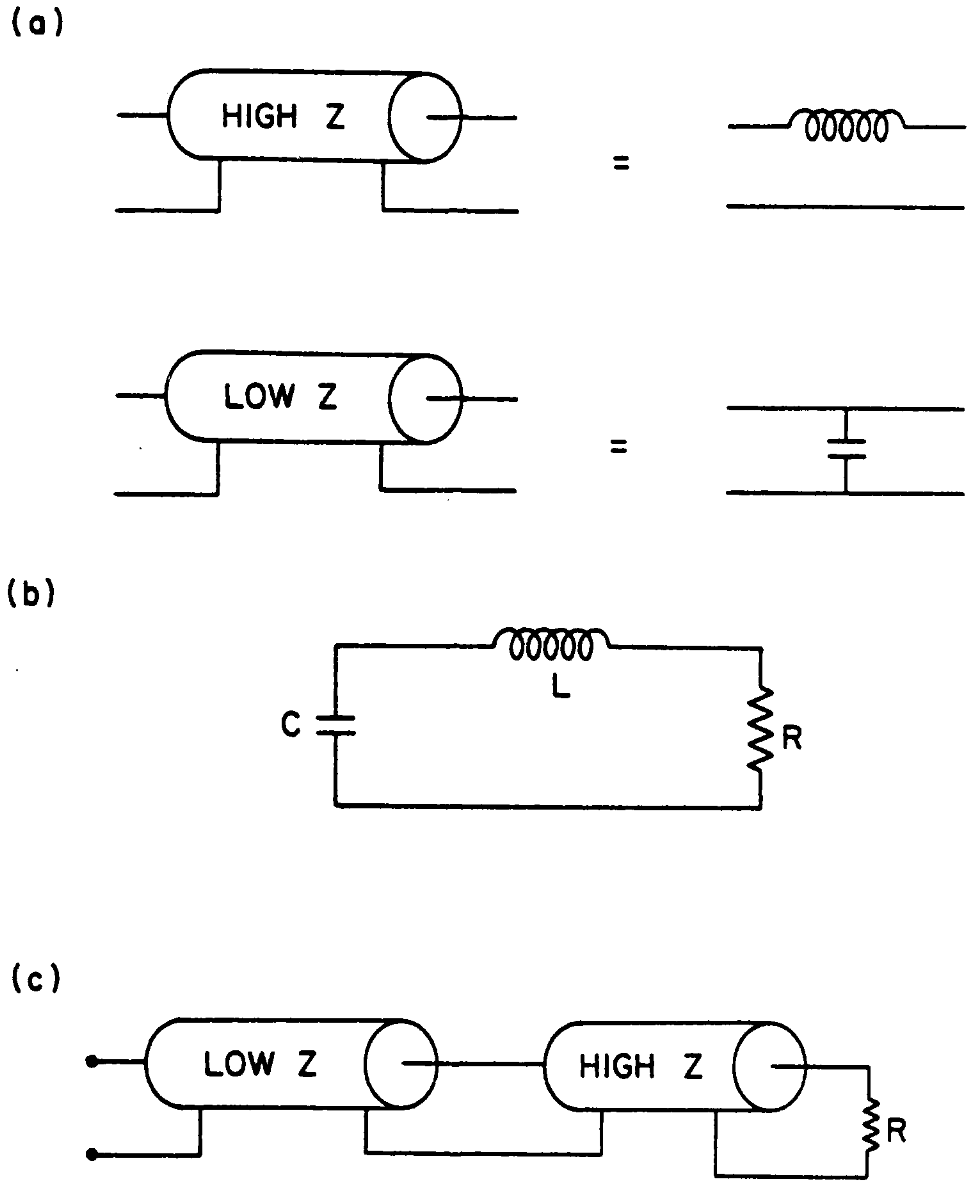



Fig. 2: (a) Representation of reactive components by transmission line elements (b) simple RLC circuit (c) transmission line model.

appropriate time in the past, determined by the transit time through the element. The remaining 2N equations necessary to close the system describe the reflection and transmission of waves at the junctions.

As an example, consider the circuit shown in Fig. 3. A line element of impedance $Z_1$, transit time $\tau_1$, and initial charge $V_o$ is discharged at t=0 into an uncharged line of impedance $Z_2$ and transit time $\tau_2$ that is terminated by a resistance R. The eight equations for the two voltage waves are:

$$V_1(1,t) = V_2(2,t-\tau_1)$$

$$V_1(2,t) = V_2(1,t-\tau_1)$$

$$V_1(3,t) = V_2(4,t-\tau_2)$$

$$V_1(4,t) = V_2(3,t-\tau_2)$$

$$V_2(1,t) = V_1(1,t)\,\frac{\infty-Z_1}{\infty+Z_1}$$

$$V_2(2,t) = V_1(2,t)\,\frac{Z_2-Z}{Z_1+Z_2} + V_1(3,t)\,\frac{2Z_1}{Z_2+Z_1}$$

$$V_2(3,t) = V_1(3,t)\,\frac{Z_1-Z_2}{Z_1+Z_2} + V_1(2,t)\,\frac{2Z_2}{Z_1+Z_2}$$

$$V_2(4,t) = V_1(4,t)\,\frac{R-Z_2}{R+Z_2}$$

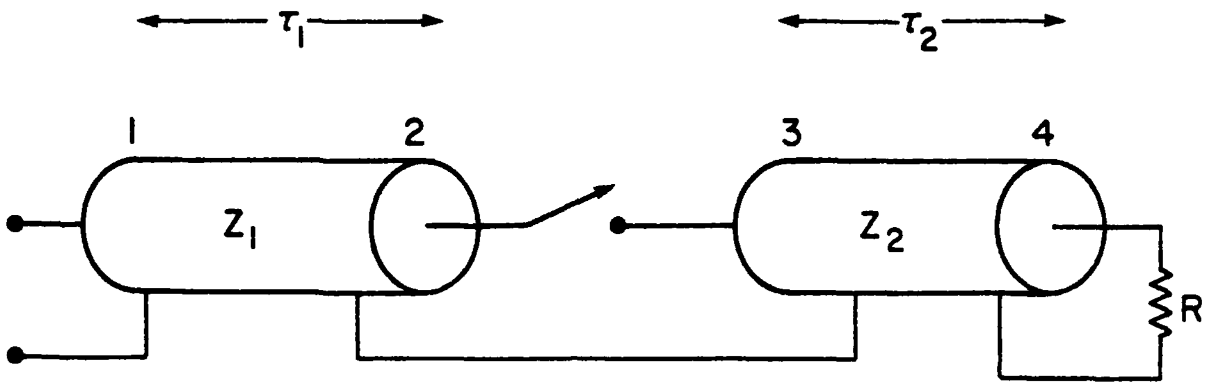



Fig. 3: The transmission line element configuration used in the example.

The first four equations are in a convenient form for programming; the last four can be put in a similarly convenient form. The junctions handled by this particular program join at most three element ends, hence, the general expression for a wave leaving a junction is:

$$V_2(I,t) = \alpha_{II}\ V_1(I,t) + \beta_{JI}\ V_1(J,t) + \beta_{KI}\ V_1(K,t)$$

where I, J and K are the element ends adjoining the junction, $\alpha_{II}$ is a reflection coefficient and $\beta_{JI}$ and $\beta_{KI}$ are transmission coefficents. The values $\alpha_{II}$, $\beta_{JI}$, $\beta_{KI}$, J and K are sufficient to specify the value of the reflected wave leaving an end I and they are stored in an array M(2N,5), in locations M(I,1) to M(I,5), respectively. In the case of a simpler junction, M(I,4) and M(I,5) are set to 1 and M(I,2) and M(I,3) are set to zero. For the example of Fig. 3, M would be given by:

| I | M(I,1) ($\alpha_{II}$) | M(I,2) ($\beta_{JI}$) | M(I,3) ($\beta_{KI}$) | M(I,4) (J) | M(I,5) (K) |
|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 1 | 1 |
| 2 | $\frac{Z_2-Z_1}{Z_1+Z_2}$ | $\frac{2Z_1}{Z_1+Z_2}$ | 0 | 3 | 1 |
| 3 | $\frac{Z_1-Z_2}{Z_1+Z_2}$ | $\frac{2Z_2}{Z_1+Z_2}$ | 0 | 2 | 1 |
| 4 | $\frac{R-Z_2}{R+Z_2}$ | 0 | 0 | 1 | 1 |

The equations describing waves leaving junctions are then all in the form:

$$V_2(I,t) = M(I,1) * V_1(I,t) + M(I,2) * V_1(M(I,4),t)$$

$$+ M(I,3) * V_1(M(I,5),t) \quad .$$

The memory requirements of this program are reduced in two ways. At each timestep, $V_1(t)$ is calculated from $V2(t-\tau)$ and V2(t) is calculated from all of the V1's entering the junctions. Thus, it is only necessary to know the value of V1 for a single timestep, and so V1 is dimensioned V1(2N). Also, it is never necessary to know the value of V2 at a time farther back in the past than the transit time of the longest element, LO, and so V2 is dimensioned V2(2N,LO). The entries in V2 are continually being written over in a cyclical fashion.

It remains necessary to incorporate initial voltages and currents. These are handled by noting that these initial standing waves are just superpositions of two traveling waves, determined by:

$$V_+ = \frac{V_o + I_o Z}{2}$$

$$V_- = \frac{V_o - I_o Z}{2}$$

as shown in Fig. 4. At the start of execution, the array V2 is back-filled to

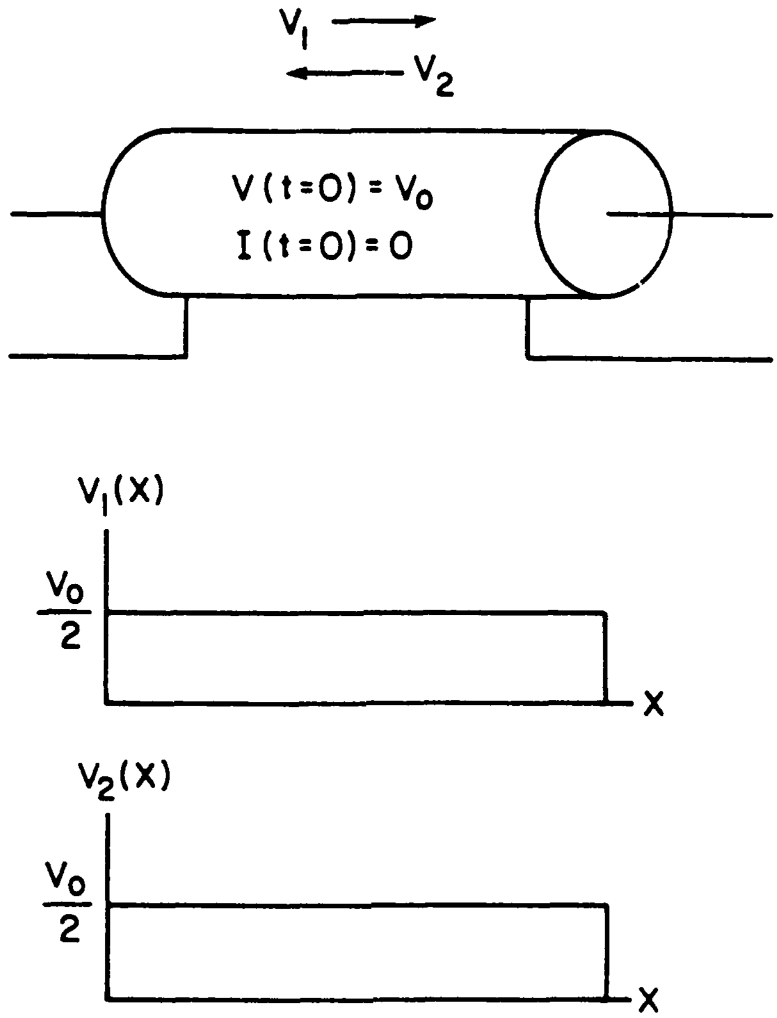



Fig. 4: The traveling wave representation of an initial standing wave voltage.

include these initial traveling waves. For example, in Fig. 3, if $\tau_1=4$, $\tau_2=6$, $V_o=10$, the array V2 would be given by:

| I | V2(I,1) | V2(I,2) | V2(I,3) | V2(I,4) |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 |
| 3 | 5 | 5 | 0 | 0 |
| 4 | 5 | 5 | 0 | 0 |
| 5 | 5 | 5 | 0 | 0 |
| 6 | 5 | 5 | 0 | 0 |

At the start, the first row in V2 corresponds to the present time and rows 3-6 correspond to times t=-4 to t=-1, respectively. After the first timestep, V1 will be given by:

| V1(1) | V1(2) | V1(3) | V1(4) |
|---|---|---|---|
| 5 | 5 | 0 | 0 |

and V2 will be given by:

| I | V2(I,1) | V2(I,2) | V2(I,3) | V2(I,4) |
|---|---|---|---|---|
| 1 | 5 | $5 * \frac{Z_2-Z_1}{Z_2+Z_1}$ | $5 * \frac{2Z_2}{Z_2+Z_1}$ | 0 |
| 2 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 4 | 5 | 5 | 0 | 0 |
| 5 | 5 | 5 | 0 | 0 |
| 6 | 5 | 5 | 0 | 0 |

At this point, the second row corresponds to the present time, the first to t=-1 and rows 4-6 to times t=-4 to t=-2, respectively.

The versatility of this program stems from the fact that the configuration is alternately considered to be a collection of separate elements and then a collection of separate junctions. This approach is also used to facilitate data entry. First the properties of each element are entered in turn, then the junction properties are entered. The junctions that can be used in this program are shown in Fig. 5. The properties of the junctions are stored in an array J(N+1,4) (a configuration of N elements will have in general N+1 junctions). J(I,1) is the junction number and J(I,2) is the first element end entered. J(I,3) is the second element end (0 for a type 1 junction) and J(I,4) is either the third element end or the value of the junction resistance (or 0 for a type 2 junction). For the example in Fig. 3, J is given by:

| I | J(I,1) | J(I,2) | (J(I,3) | J(I,4) |
|---|---|---|---|---|
| 1 | 1 | 1 | 0 | $10^6$ (or any large number) |
| 2 | 2 | 2 | 3 | 0 |
| 3 | 1 | 4 | 0 | R |

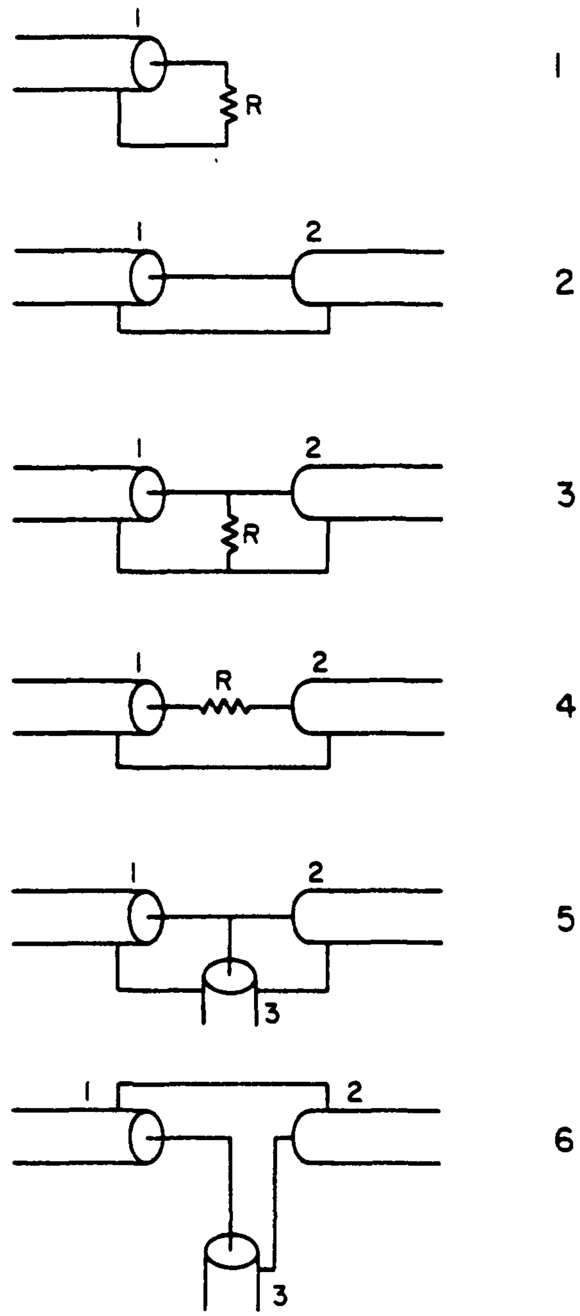



Fig. 5: The junctions used in this program.

For the purpose of illustration, a simplified version of the program is shown in Appendix B. As can be seen, the following variables are used:

| | |
|---|---|
| N | Number of elements |
| T1 | Total time |
| WO | Number of plots desired |
| L(N) | Transit times of elements |
| Z(N) | Impedances of elements |
| VO(N) | Initial voltages of elements |
| IO(N) | Initial currents of elements |
| W1(WO) | End numbers for which plots of voltage are desired. |

The program is easy to use. The first step is to number the junctions, elements and element ends. The only restriction on numbering is that element I must have its ends numbered 2I-1 and 2I. After entering the numbers of elements, timesteps and plots desired, the element properties are entered sequentially, followed by the junction properties and finally the element ends where plots are desired. The mnemonic given for the type 6 junction (line 490) means that the first element end to be entered is the one that has its hot connected to an opposing hot and its ground connected to an opposing ground, etc. The element ends for the type 6 junction shown in Fig. 5 would be entered in the order 1,2,3.

This method of data entry allows straightforward input of arbitrarily complicated configurations. It can be seen that the longest section of the program is the transformation of J to M, which only needs to be done once.

The actual program execution is contained in the short section at the end. In that section T0 is a pointer which indicates the row in V2 corresponding to the present time; it cycles from 1 to L0 continually.

The version of BERTHA currently in use has several features in addition to the sample program described above that permit configurations to be modified during program execution. Junction types 7-9, shown in Fig. 6, are switches. The closing [opening] switches are just resistances whose values change from infinite [zero] to zero [infinity] at a preset time or voltage. These are simple to incorporate as switching just corresponds to a multiplication of the reflection coefficient by -1. It should be noted that the inductive and/or capacitive characteristics of a real switch may be modeled by adding suitable short line elements as shown in Fig. 7. To take into account more detailed switch characteristics such as resistive risetimes, however, variable resistances (described next) must be used.

The values of the resistances in junction types 1, 3 and 4 may be varied during program execution by external subroutines. The time, voltage across and current through each resistance are supplied to the subroutines at each timestep. The line element impedances may be varied in exactly the same fashion.

External waveforms may be fed into the configuration from any Type 1 junction. In this case, the injected waveform is added to reflections from the junction resistance. By convention, the program assumes that the supplied waveform is the open circuit voltage, $V_o(t)$, that would have been measured at the end of a line of impedance equal to the junction resistance R. The

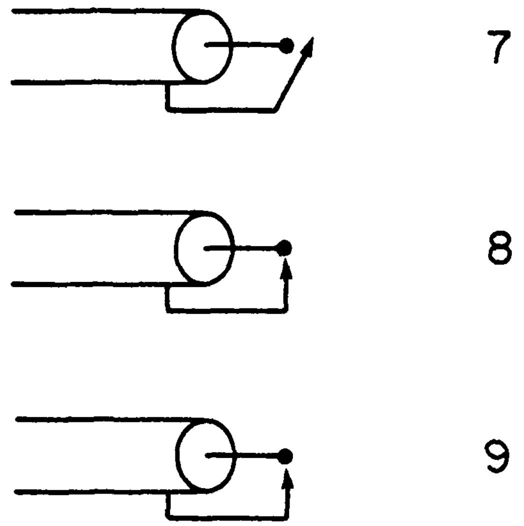



Fig. 6: Junctions used to represent switches: (7) command opening; (8) command closing; (9) self-break closing.

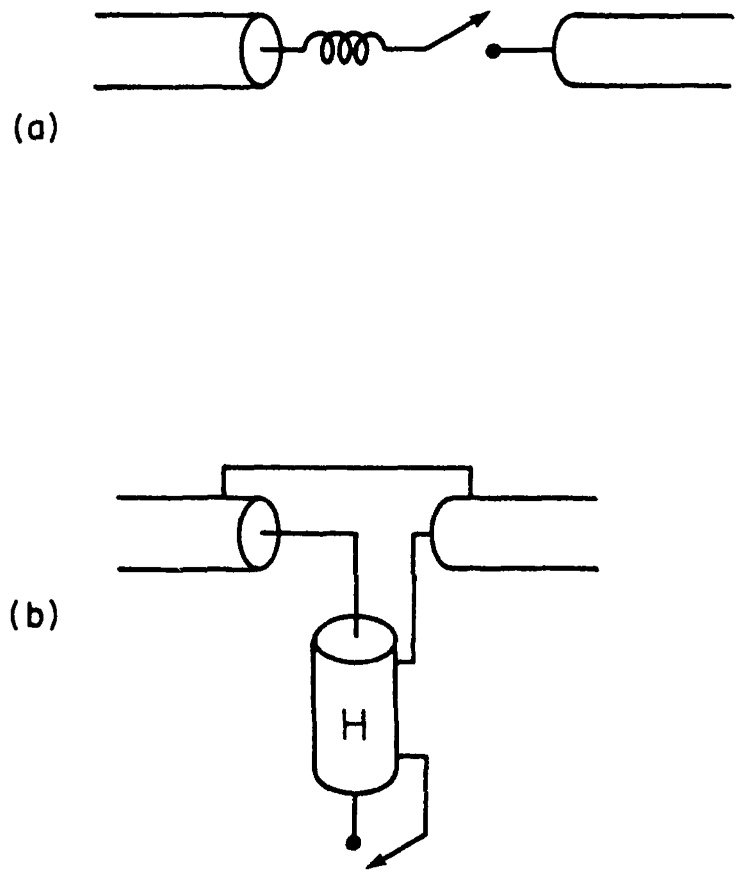



Fig. 7: The switch inductance (a) is modeled by a short line element (b).

voltage that is actually fed in from the junction is that which would have been transmitted to a line element of impedance $Z_o$, i.e,

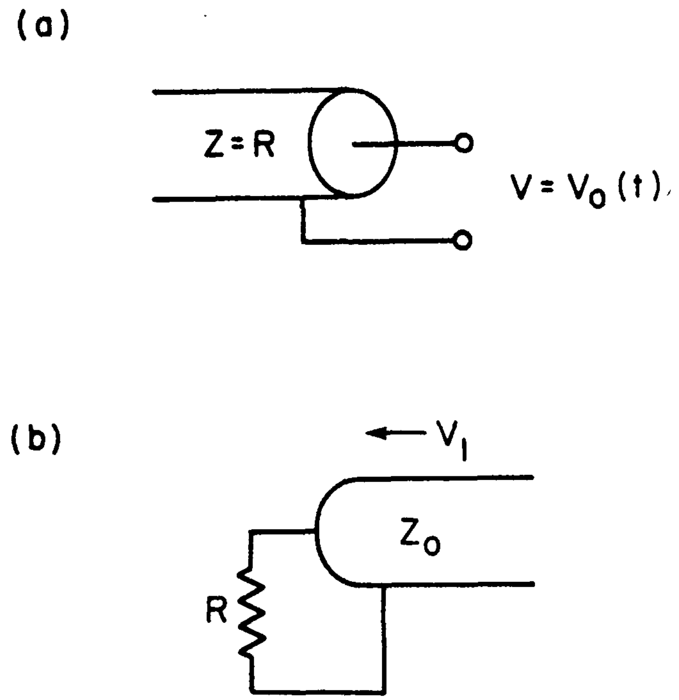
$$V_o(t)\,\frac{Z_o}{Z_o+R}\ ,$$

as shown in Fig. 8.

Output plots are available for the standing wave voltage, current, impedance, power flow and energy flow at any element end. It is also possible to save for plotting any values calculated in the external subroutines, such as the radius (at each timestep) of an imploding foil.

The full program listing is shown in Appendix C.

Variable impedance elements are indicated to the program by typing a "V" after the element (initial) impedance. Variable resistances are indicated in the same manner. If an external waveform is to be fed into a Type 1 junction, an "I" should be typed after the junction resistance. (Both features may be combined at a Type 1 junction by typing "VI" or "IV".) (This particular version has a limit of nine input pulses, variable resistances and variable impedance elements, each.) It is assumed that the subroutines for variable resistances and impedances and the values of the external waveforms are stored on disk prior to running the program; it is the file names that are entered. The starting time and plotstep (line 430) refer to the output plots - values are only saved and plotted at every plotstep. The Type 10 junction (line 1210) is a minor convenience which allows a string of Type 2 junctions to be entered at once by entering the end numbers at the beginning and end of the string. When a configuration includes loops (Fig. 9) the number of junctions will be less than N+1. In this case, zeros should be entered as the junction types for the missing junctions.




$$V_2 = V_1 \frac{R - Z_0}{R + Z_0} + V_0(t)\,\frac{Z_0}{R + Z_0}$$

Fig. 8: The waveform supplied is assumed to be an open circuit voltage (a); the injected waveform is this open circuit voltage multiplied by $Z_0/(R+Z_0)$.

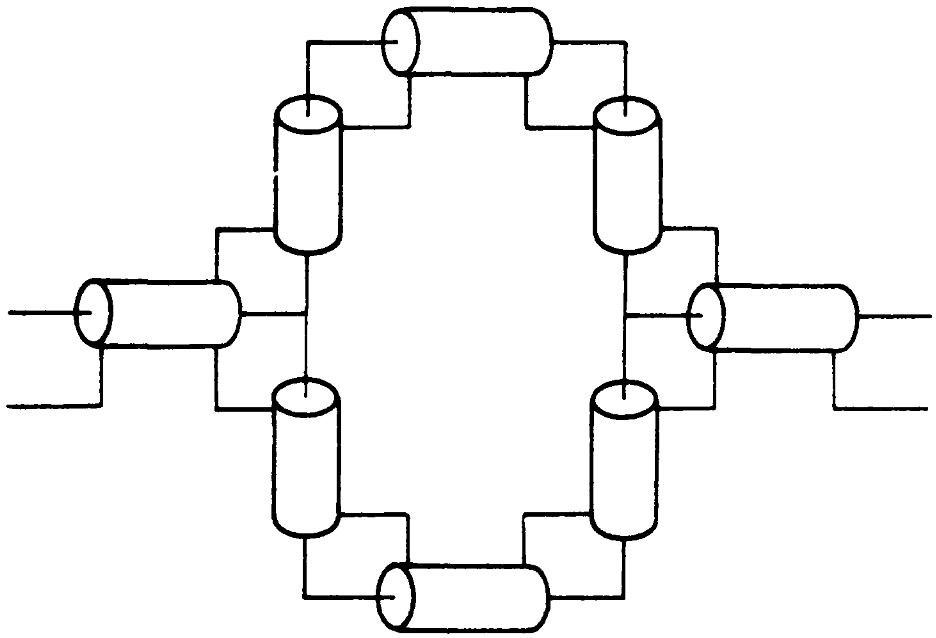


Fig. 9: An example of a configuration which includes a loop.

For each output plot, the end number should be entered, followed by "V", "I", "Z", "P" or "E", depending on whether the plot is to be of (standing wave) voltage, current, impedance, power flow or energy flow, respectively. Zero should be entered as the end number of plots of values calculated in the external subroutines, followed by a single symbol which will serve to identify the plot. For each of these values to be plotted, a program line is needed in the subroutine, and the values are then saved for plotting in the order in which they were calculated. This is all illustrated in the fourth example given in the next section.

Before execution, any necessary subroutines and waveforms are pulled from the disk. At every timestep during execution, the switches are examined and flipped if necessary, input pulses are added in, values are stored for plots if needed and the variable resistances and impedances are changed. Then the J → M segment of the program (which is written here as a subroutine) is called for every junction for which the reflection and transmission coefficients will have changed - i.e., those junctions that contain variable resistances or that border variable impedance elements. The bookkeeping necessary to keep track of these junctions is handled by the arrays P1 (a list of junctions where pulses are to be injected), Q1 (variable impedance elements), R1 (variable resistances) and J1 (a list of junctions whose coefficients must be updated). The intermediate arrays J9 and Q9 are used to form J1. The switch parameters are stored in the array S(S0,3), where S0 is the number of switches in the configuration. S(I,1) is the end number of the switch, S(I,2) is 1 for a command triggered and 0 for a self breaking switch and S(I,3) is either the switching time or the breakdown voltage. At each timestep, either the time or voltage (depending on the type of switch) is compared with S(I,3). If the switch is to be flipped, the corresponding reflection coefficient is

multiplied by -1 and then S(I,3) is set to a very large number to prevent the switch from being flipped again.

The variables N1, N2, R2, V6, and I6 are furnished to each variable resistance subroutine. N1 and N2 are the two end numbers in the junction containing the resistance (N1 is the first junction number that was entered and N2 has no meaning for a type 1 junction.) R2 is the current value of the junction resitance and V6 and I6 are the voltage across and current through the resistance, respectively. The new value of the resistance calculated in the subroutine should replace the old value in R2. The variables N1, N2 and Q2 are furnished to each variable impedance subroutine. N1 and N2 refer to the end numbers of the variable impedance line element and Q2 is the current value of the element impedance; again, the calculated new value should replace this in Q2.

When the impedance of a line element is changed, the values of the traveling wave voltages on that element must in general be changed to take into accout the IdL/dt and VdC/dt terms. Since the change in element impedance is assumed instantaneous at each timestep, no charge or magnetic flux can flow into the element during the change. The charge, Q, and flux, $\phi$, are given by:

$$Q = CV = \frac{\tau}{Z} (V_1+V_2)$$

$$\phi = LI = \tau(V_1-V_2)$$

The requirement of charge and flux conservation determines the new values of $V_1$ and $V_2$:

$$V_1' = \tfrac{1}{2}\left[V_1 \left(\frac{Z'}{Z} + 1\right) + V_2 \left(\frac{Z'}{Z} - 1\right)\right]$$

$$V_2' = \tfrac{1}{2}\left[V_2 \left(\frac{Z'}{Z} + 1\right) + V_1 \left(\frac{Z'}{Z} - 1\right)\right]$$

where primes denote the new values. $V_1$ and $V_2$ must be corrected for each timestep of the element length. A general subroutine for this is given in Appendix 4. This correction is greatly simplified when the variable impedance element is used to model a changing lumped parameter element. In this case:

$$V_1' = V_1$$

$$V_2' = V_2$$

for an inductor, and

$$V_1' = V_1 \, Z'/Z$$

$$V_2' = V_2 \, Z'/Z$$

for a capacitor.

## EXAMPLES

Consider the simple RLC circuit shown in Fig. 10a, with the corresponding line element configuration shown in Fig. 10b. The data entry and output are shown in Fig. 10c. The exact analytical solution is also shown on the output plot, and the agreement is seen to be excellant. The accuracy of approximating reactive components by short line elements is related to the parameter $T/\tau$, where $\tau$ is the line element transit time and T refers to the

time constant of the circuit. A larger $T/\tau$ will give a better approximation at the expense of added execution time, since in general the line elements corresponding to reactive elements will be one timestep long. For the configuration of Fig. 10b, $T/\tau = 10$ . The output for a similar configuration with 5 ns long elements and correspondingly different impedances, for which $T/\tau = 2$, is shown in Fig. 10d for comparison.

A second example - an RC circuit with a changing capacitance - is shown in Fig. 11. Note that the traveling wave voltages on the variable impedance element are changed at each timestep in the subroutine. Again, the exact solution:

$$V = (1 + .2t)^{-2}$$

is shown on the output plot and the agreement is excellant.

As a third example, consider the hypothetical magnetically insulated transmission line experiment shown in Fig. 12a. A charged pulse line is connected to a short section of uncharged line at t=o by the closing of an output switch. This short line is connected to a short magnetically insulated section which is terminated by an inductive load. The parameters of the various segments are indicated in the figure and the experiment could be modeled by the configuration in Fig. 12b. The resistor in junction 5 represents losses in the magnetically insulated section. Assume that the following simple model is to be used for the magnetically insulated section:

the loss (i.e. shunt current through the resistor) is zero if the current through the line, $I_o$, exceeds the self limiting current,[5] which happens to be

$$I_{SL} = 56,600\ \gamma\ \ln\ [\gamma + (\gamma^2-1)^{1/2}]$$

$$\gamma = 1 + V[MV]/.510$$

for this case. If $I_o < I_{SL}$, then the loss current will adjust itself so that the current into the line, $I_{IN}$, is equal to $I_{SL}$, i.e.,

$$\begin{aligned} I_{shunt} &= 0 & I_o > I_{SL} \\ &= I_{SL} - I_o & I_o < I_{SL} \end{aligned}$$

The variable resistance subroutine for this model is shown in Fig. 12c. The data entry and output for this example are shown in Fig. 12d.

An imploding foil driven by a capacitor bank[3] is given as the last example. The circuit inductance may be expressed as:

$$L = L_o \ell n(R/r)$$

where r is the foil radius and R is chosen to include both the foil and external circuit inductances. The equations describing the implosion are then:

$$\frac{d^2r}{dt^2} = -\ .01\ \frac{h}{m}\,\frac{I^2}{r}$$

$$\frac{dL}{dt} = -\ \frac{2h}{r}\,\frac{dr}{dt}$$

where h is the foil height in cm, m is the foil mass in gm, r is in cm, L in nH, I in MA and t in μs. For the example here, r(t=0)=7, h=2, M=.02 and the foil is driven by a 200 μF capacitor bank which is charged to 70 kV (these are typical of the parameters in Ref. 3). The circuit, configuration, foil subroutine, input and output are shown in Fig. 13.

Cumulative errors may result when the element impedances are changed during the course of program execution. For example, in the present case, assume that the calculated foil radius is too small (and the inductance too large) at a given timestep. The larger inductance will tend to decrease the calculated foil current over the correct value on the next timestep, while the smaller radius will result in a greater foil acceleration for a given current. These effects will compete but for a sufficiently small radius the latter will dominate and the calculated solution will diverge from the correct result. As a test for this, the conservation of energy and magnetic flux are checked in this example. The foil (kinetic and magnetic) energy is calculated in the subroutine and compared to the flow of electrical energy into the foil that is calculated in the main program. The instantaneous value of the flux, LI, is compared with the integrated flow of flux into the foil, $\int V dt$, both of which are calculated in the subroutine. The variable W3 refers to the row in the plot array, W, for each particular calculated quantity. Note that during input the subroutine plots are entered after the standard plots.

Runs for two different timesteps are shown, corresponding to a foil collapse in 30 and 300 timesteps. Note that the energy and magnetic flux are more closely conserved for the smaller timestep but there is little change in the calculated values of the foil radius and current as the timestep is decreased.

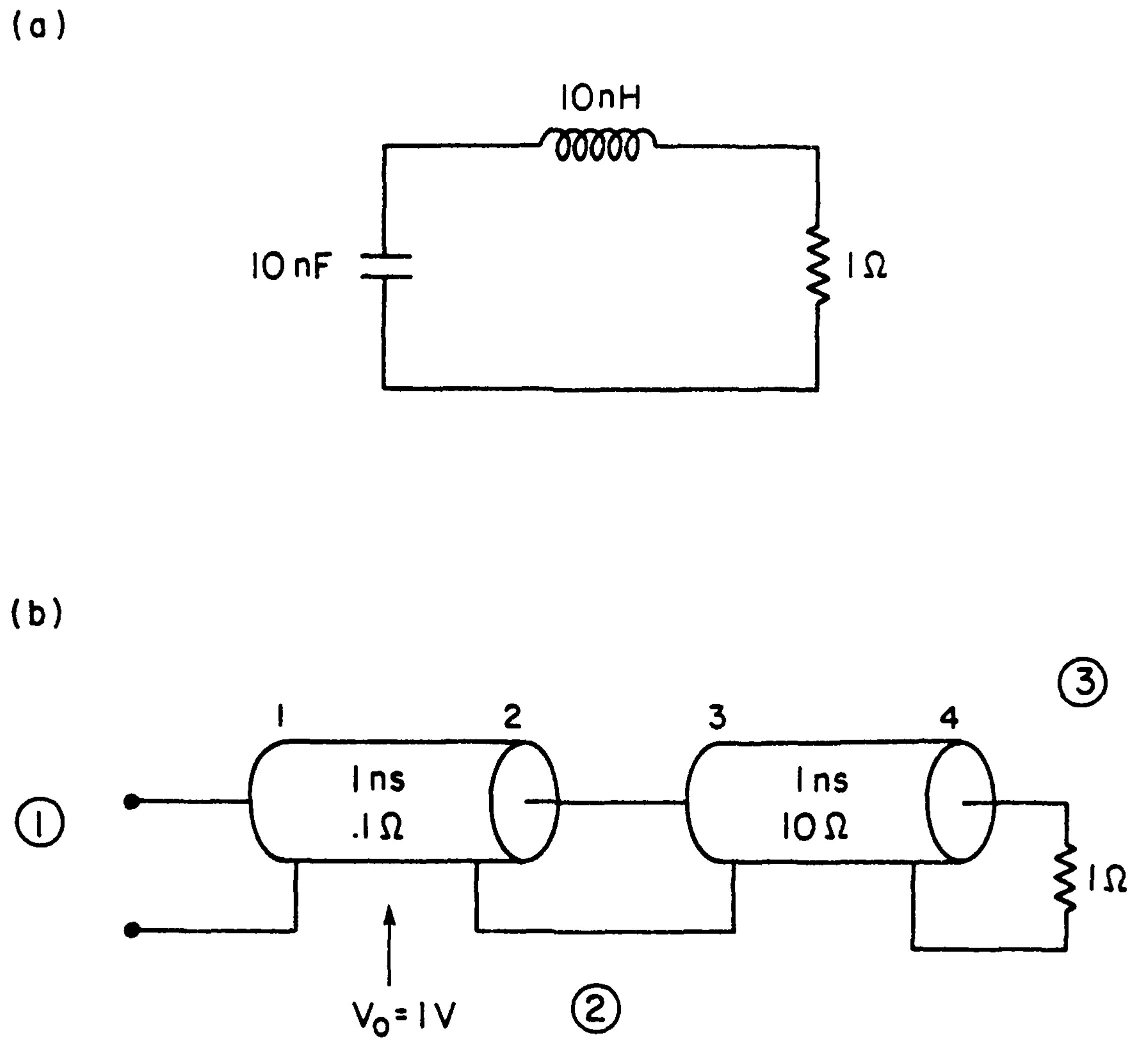



Fig. 10: (a) an RLC circuit (b) the transmission line model.

```
Enter the number of elements: 2
Enter total time, timestep, [starting time], [plotstep]:  100,1
Enter the total number of plots desired:  1

Enter L, Z, [V0], [I0] for element 1 :  1,.1,1
Enter L, Z, [V0], [I0] for element 2 :  1,10

Enter the junction type for junction 1 :  1
Enter the end number and resistance:  1,1E6
Enter the junction type for junction 2 :  2
Enter the end numbers:  2,3
Enter the junction type for junction 3 :  1
Enter the end number and resistance:  4,1

Enter the end number and V, I, P, E or Z for plot 1:  1,V
```

Fig. 10c: Input and output for this configuration; $T/\tau = 10$. The smooth curve is the exact result.

BERTHA - NRL GAMBLE GROUP TRANSMISSION LINE CODE CONFIGURATION LISTING

CONFIG. NAME: 02-MAY-83 09:01:35

| QUANTITY | VARIABLE NAME | VALUE |
|---|---|---|
| Number of elements | N | 2 |
| Total time | T1 | 100.000 |
| Timestep | T2 | 1.000 |
| Waveform start time | T3 | 0.000 |
| Waveform plot step | T4 | 1 |
| Number of plots | W0 | 1 |
| Number of input pulses | P0 | 0 |
| Number of var impedances | O0 | 0 |
| Number of var loads | R0 | 0 |
| Number of switches | S0 | 0 |

| ELEMENT NO | L | Z | V0 | I0 |
|---|---|---|---|---|
| 1 | 1.00E+000 | 1.00E-001 | 1.00E+000 | 0.00E+000 |
| 2 | 1.00E+000 | 1.00E+001 | 0.00E+000 | 0.00E+000 |

| JUNC # | J(I,1) TYPE | J(I,2) QUANT | J(I,3) QUANT | J(I,4) QUANT |
|---|---|---|---|---|
| 1 | 1 Resist | 1 End Num | 0 ------- | 1.00E+006 Resist |
| 2 | 2 Simple | 2 End Num | 3 End Num | 0 ------- |
| 3 | 1 Resist | 4 End Num | 0 ------- | 1.00E+000 Resist |

| INPUT PULSE | END | VAR IMPEDANCE | ELT | VAR RESISTANCE | END |
|---|---|---|---|---|---|
| 000000 | 0 | 000000 | 0 | 000000 | 0 |

| PLOT LISTING | END | NUMBER | TYPE |
|---|---|---|---|
| Plot No.: 1 | | 1 | Voltage |

Fig. 10d: Output for the same configuration with a $T/\tau$ of 2.

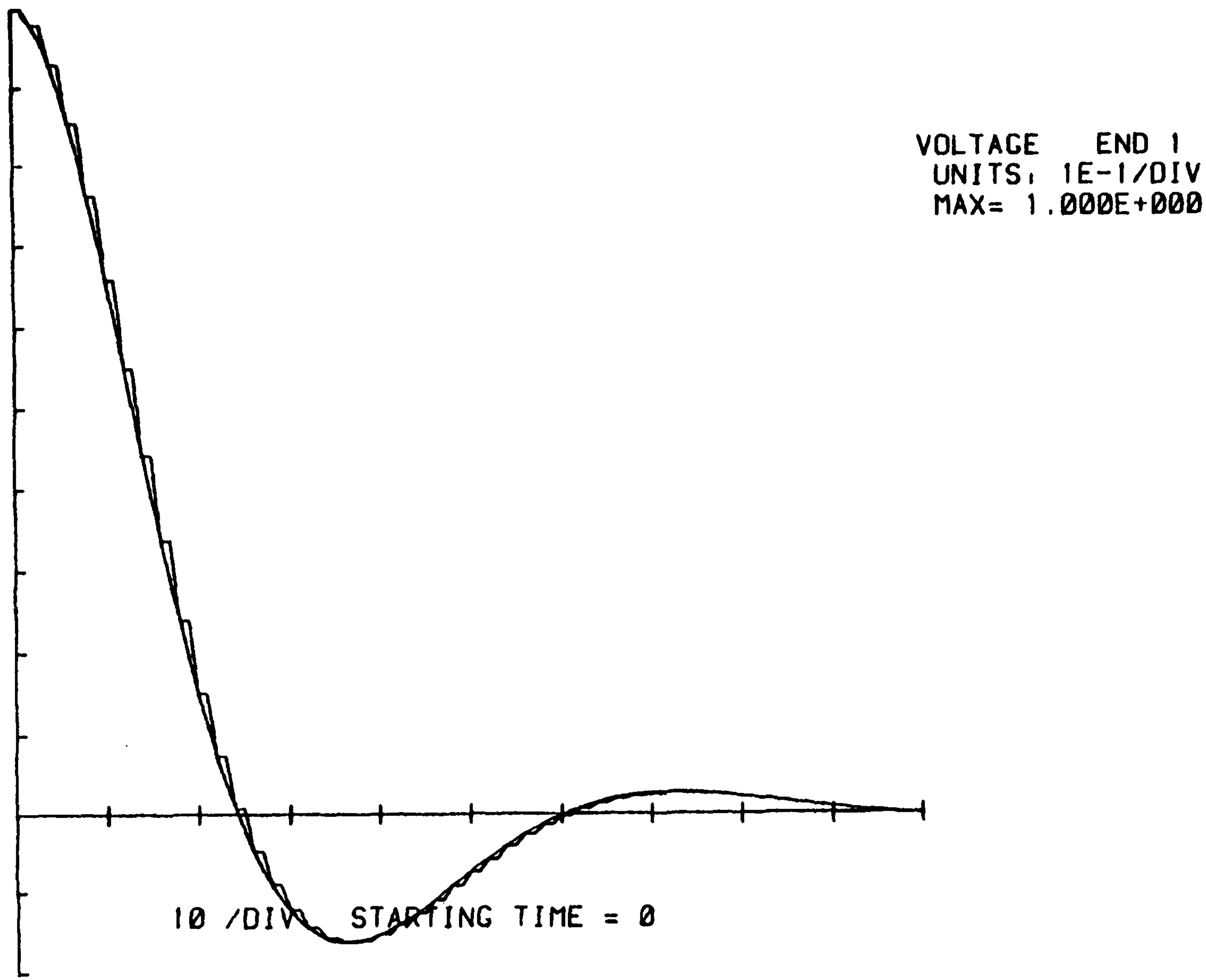



Fig. 10d (Cont'd): Output for the same configuration with a $T/\tau$ of 2.

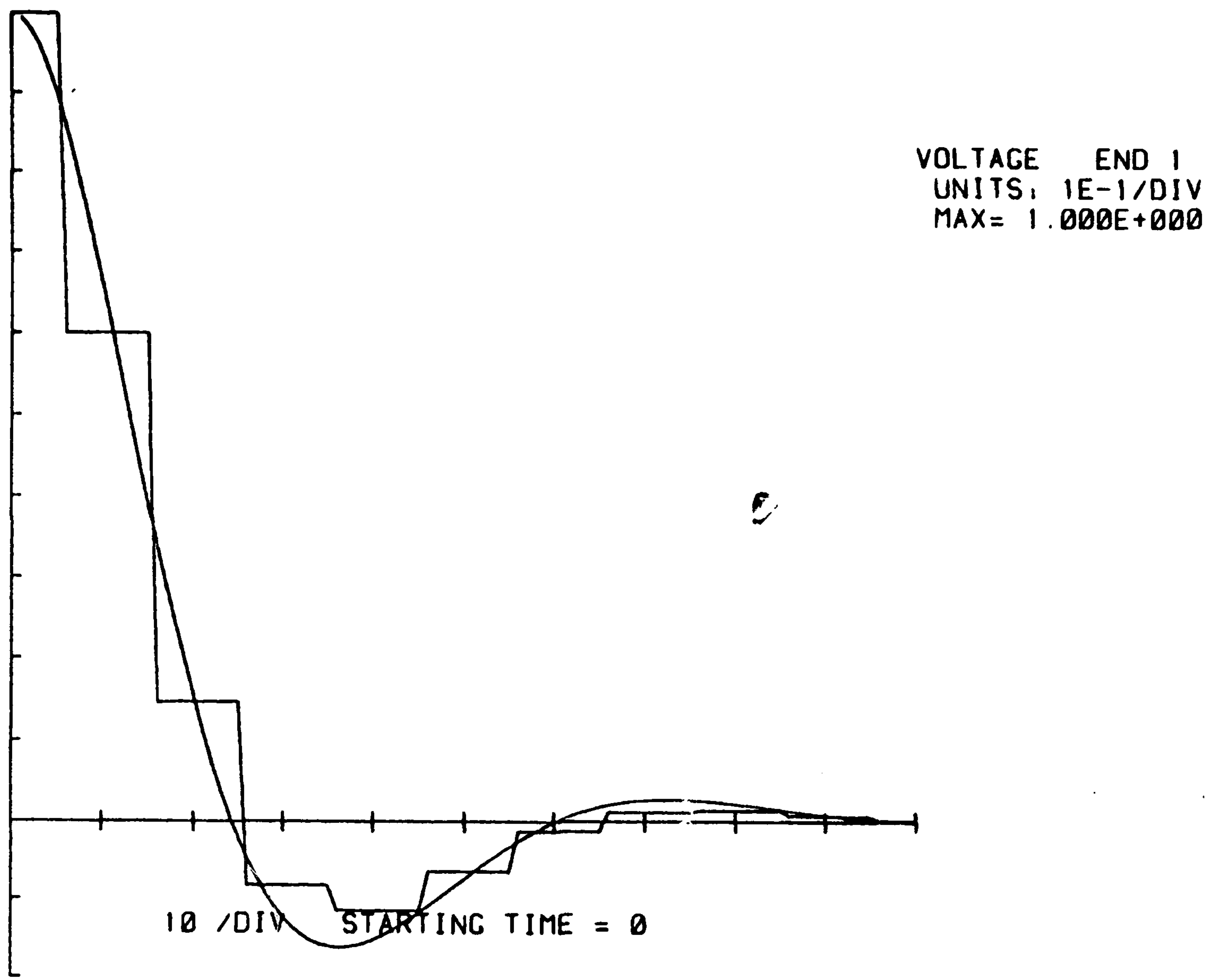



Fig. 10d (Cont'd): Output for the same configuration with a $T/\tau$ of 2.

(a)

(b)

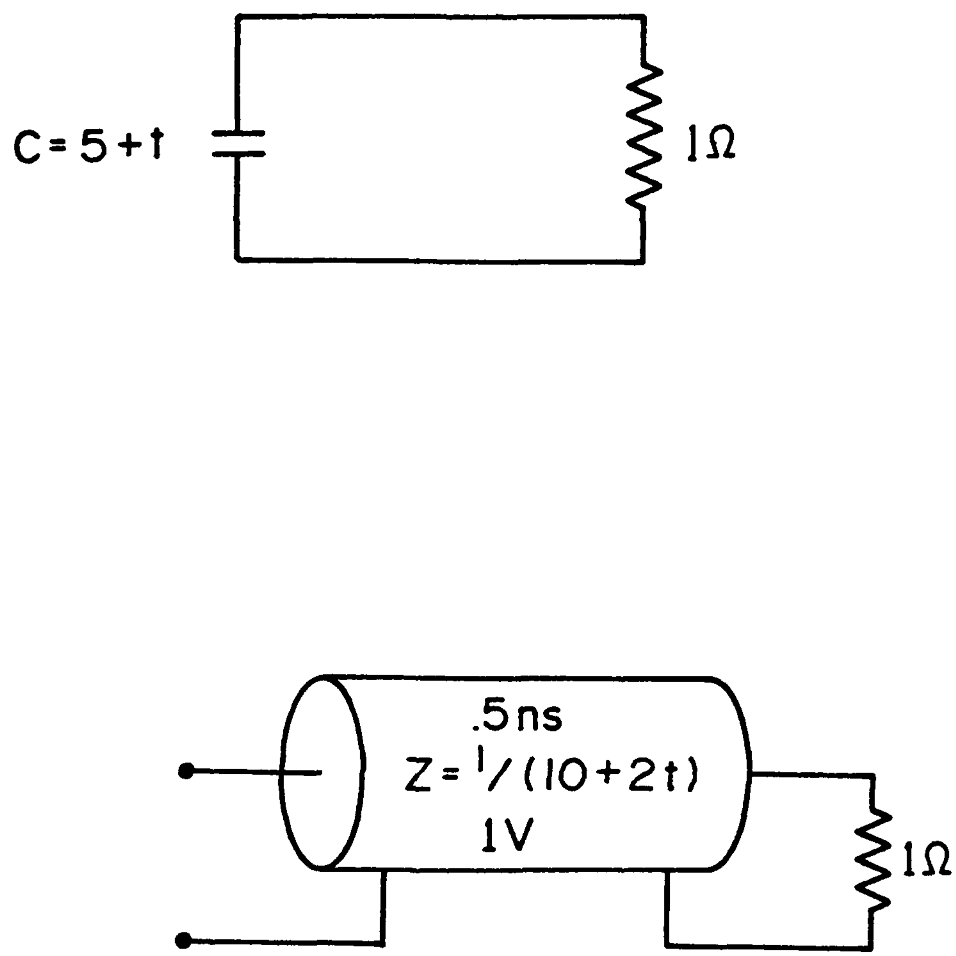



Fig. 11: (a) A circuit with a changing capacitance (b) transmission line model.

```
3760 REM-------SUBROUTINE CTEST1
3761 O3=0.5/(5+T*T2)
3762 FOR I1=1 TO L0
3763 V2(N1,I1)=V2(N1,I1)*O3/O2
3764 V2(N2,I1)=V2(N2,I1)*O3/O2
3765 NEXT I1
3766 O2=O3
3767 REM-----END OF SUBROUTINE
```

Fig. 11c: The subroutine used to model the capacitance.

```
Enter the number of elements:  1
Enter total time, timestep, [starting time], [plotstep]:  30,.5
Enter the total number of plots desired:  1

Enter L, Z, [V0], [I0] for element 1 :  .5,.1V,1
Enter the name of the variable impedance subroutine:  CTEST1

Enter the junction type for junction 1 :  1
Enter the end number and resistance:  1,1E6
Enter the junction type for junction 2 :  1
Enter the end number and resistance:  2,1

Enter the end number and V, I, P, E or Z for plot 1:  2,V
```

Fig. 11d: Input and output for this configuration. Again, the smooth curve is the exact result.

```
BERTHA - NRL GAMBLE GROUP TRANSMISSION LINE CODE   CONFIGURATION LISTING

CONFIG. NAME:         02-MAY-83 16:45:26

QUANTITY                             VARIABLE NAME              VALUE
Number of elements                         N                      1
Total time                                 T1                    30.000
Timestep                                   T2                     0.500
Waveform start time                        T3                     0.000
Waveform plot step                         T4                     1
Number of plots                            W0                     1
Number of input pulses                     P0                     0
Number of var impedances                   O0                     1
Number of var loads                        R0                     0
Number of switches                         S0                     0

ELEMENT NO        L            Z            V0          I0
    1         5.00E-001    1.00E-001    1.00E+000   0.00E+000

JUNC #    J(I,1) TYPE    J(I,2) QUANT     J(I,3) QUANT     J(I,4) QUANT
   1        1  Resist      1  End Num      0  ------- 1.00E+006 Resist
   2        1  Resist      2  End Num      0  ------- 1.00E+000 Resist

INPUT PULSE  END        VAR IMPEDANCE  ELT        VAR RESISTANCE  END
  000000      0            CTEST1        1           000000         0

PLOT LISTING       END   NUMBER       TYPE
Plot No.:  1              2           Voltage
```

Fig. 11d (Cont'd): Input and output for this configuration. Again, the smooth curve is the exact result.

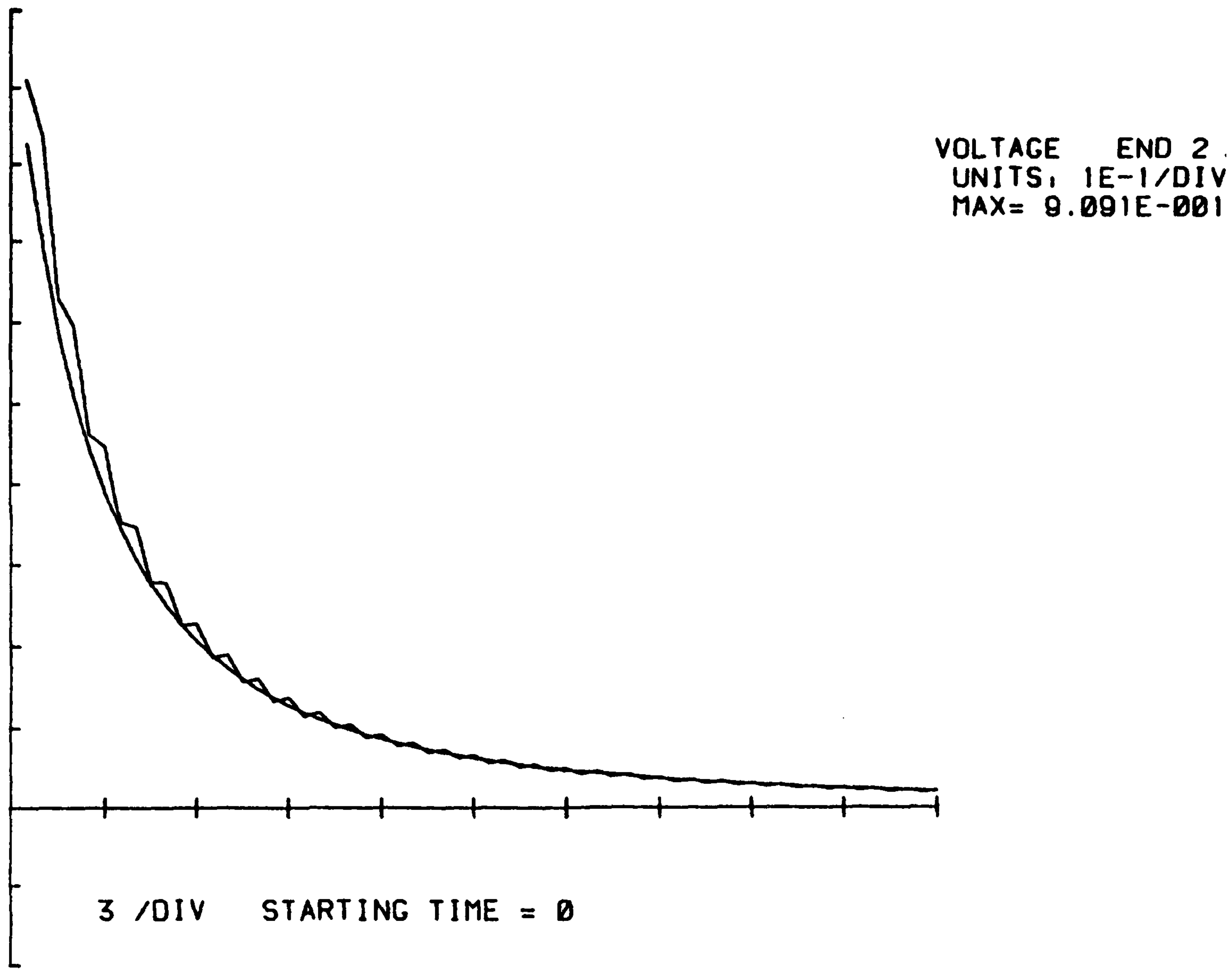
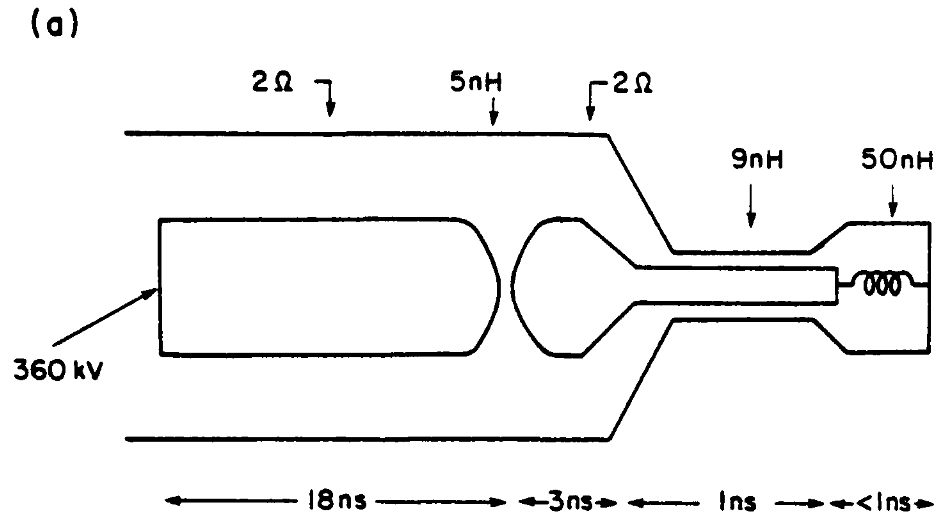



Fig. 11d (Cont'd): Input and output for this configuration. Again, the smooth curve is the exact result.



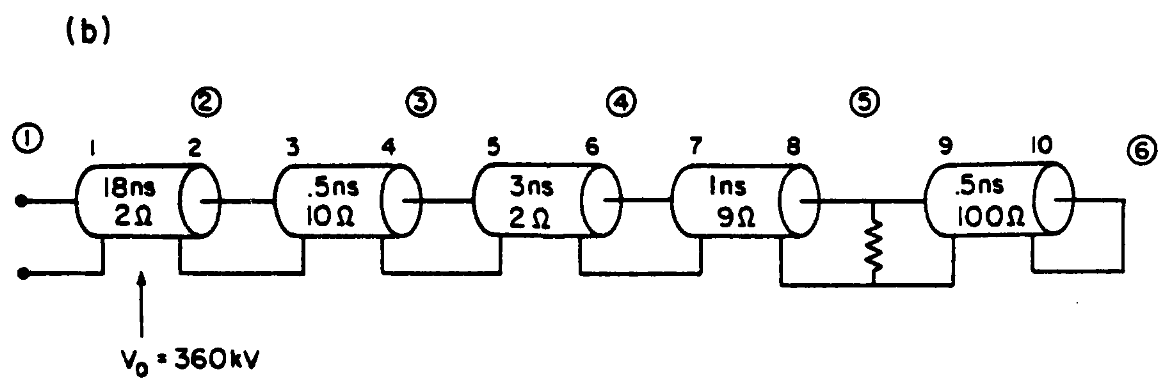




Fig. 12: (a) Short magnetically insulated transmission line experiment (b) transmission line model.

```
4660 REM ------- SUBROUTINE MILOSS
4661 R2=100000
4662 I7=-(V1(N2)-V2(N2,T0))/Z2
4663 G1=1+(V6 MAX 0)/510000
4664 G2=(G1↑2-1)↑0.5
4665 I8=510000/9*G1*LOG(G1+G1*G2)
4666 IF I7>I8 OR I8=0 THEN 4668
4667 R2=V6/(I8-I7)
4668 REM-----END OF SUBROUTINE
```

Fig. 12c: The subroutine used to model the MITL loss current.

```
Enter the number of elements:  5
Enter total time, timestep, [starting time], [plotstep]:  100,.5
Enter the total number of plots desired:  2

Enter L, Z, [V0], [I0] for element 1 :  18,2,360000
Enter L, Z, [V0], [I0] for element 2 :  .5,10
Enter L, Z, [V0], [I0] for element 3 :  3,2
Enter L, Z, [V0], [I0] for element 4 :  1,9
Enter L, Z, [V0], [I0] for element 5 :  .5,100

Enter the junction type for junction 1 :  1
Enter the end number and resistance:  1,1E6
Enter the junction type for junction 2 :  10
Enter the initial and final end numbers for type 2 fill:  2,7
Enter the junction type for junction 5 :  3
Enter the end numbers and resistance:  8,9,1E6V
Enter the name of the variable resistance subroutine:  MILOSS
Enter the junction type for junction 6 :  1
Enter the end number and resistance:  10,0

Enter the end number and V, I, P, E or Z for plot 1:  8,I
Enter the end number and V, I, P, E or Z for plot 2:  10,I
```

Fig. 12d: Input and output for this configuration.

BERTHA - NRL GAMBLE GROUP TRANSMISSION LINE CODE CONFIGURATION LISTING

CONFIG. NAME: 17-JUN-83 14:07:43

| QUANTITY | VARIABLE NAME | VALUE |
|---|---|---|
| Number of elements | N | 5 |
| Total time | T1 | 100.000 |
| Timestep | T2 | 0.500 |
| Waveform start time | T3 | 0.000 |
| Waveform plot step | T4 | 1 |
| Number of plots | W0 | 2 |
| Number of input pulses | P0 | 0 |
| Number of var impedances | O0 | 0 |
| Number of var loads | R0 | 1 |
| Number of switches | S0 | 0 |

| ELEMENT NO | L | Z | V0 | I0 |
|---|---|---|---|---|
| 1 | 1.80E+001 | 2.00E+000 | 3.60E+005 | 0.00E+000 |
| 2 | 5.00E-001 | 1.00E+001 | 0.00E+000 | 0.00E+000 |
| 3 | 3.00E+000 | 2.00E+000 | 0.00E+000 | 0.00E+000 |
| 4 | 1.00E+000 | 9.00E+000 | 0.00E+000 | 0.00E+000 |
| 5 | 5.00E-001 | 1.00E+002 | 0.00E+000 | 0.00E+000 |

| JUNC # | J(I,1) | TYPE | J(I,2) | QUANT | J(I,3) | QUANT | J(I,4) | QUANT |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Resist | 1 | End Num | 0 | ------- | 1.00E+006 | Resist |
| 2 | 2 | Simple | 2 | End Num | 3 | End Num | 0 | ------- |
| 3 | 2 | Simple | 4 | End Num | 5 | End Num | 0 | ------- |
| 4 | 2 | Simple | 6 | End Num | 7 | End Num | 0 | ------- |
| 5 | 3 | ShnRes | 8 | End Num | 9 | End Num | 1.00E+006 | ShnRes |
| 6 | 1 | Resist | 10 | End Num | 0 | ------- | 0.00E+000 | Resist |

| INPUT PULSE | END | VAR IMPEDANCE | ELT | VAR RESISTANCE | END |
|---|---|---|---|---|---|
| 000000 | 0 | 000000 | 0 | MILOSS | 5 |

| PLOT LISTING | END NUMBER | TYPE |
|---|---|---|
| Plot No.: 1 | 8 | Current |
| Plot No.: 2 | 10 | Current |

Fig. 12d (Cont'd): Input and output for this configuration.

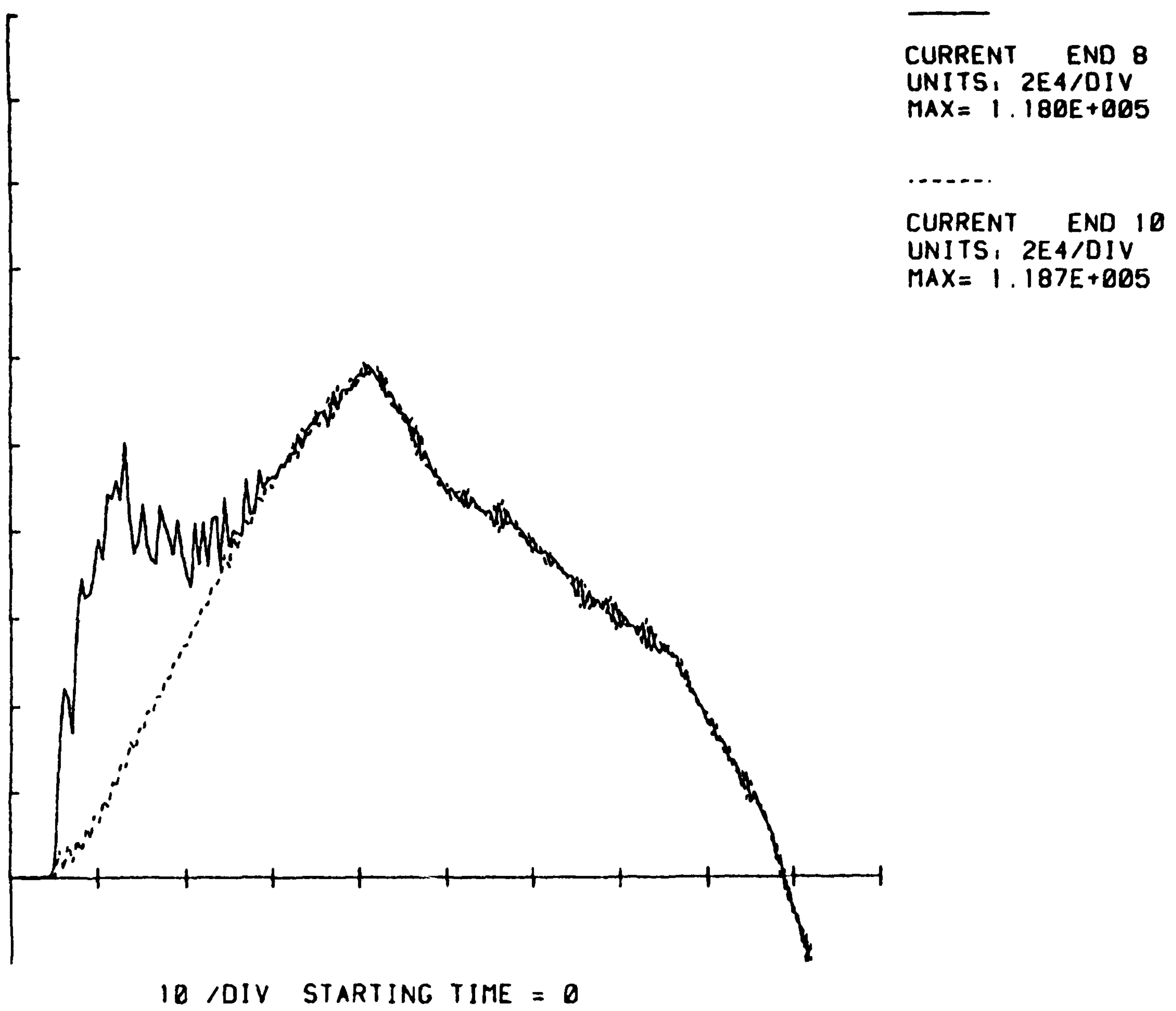
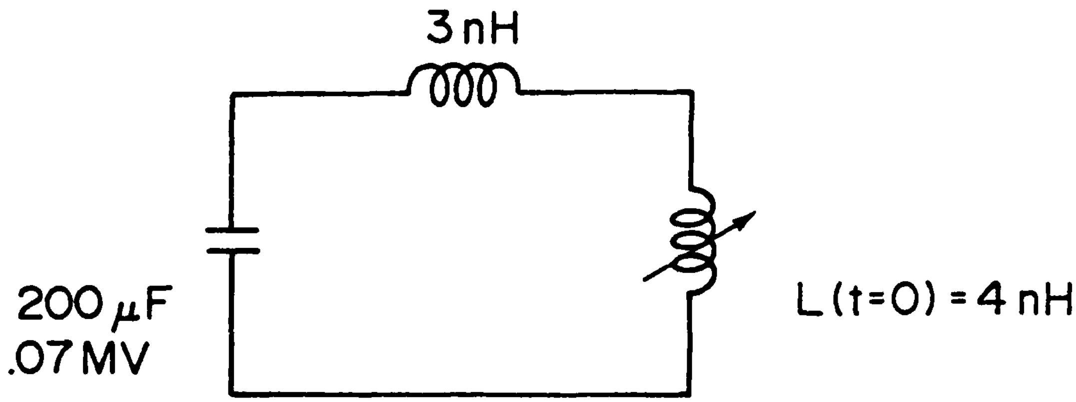



Fig. 12d (Cont'd): Input and output for this configuration.

(a)




(b)

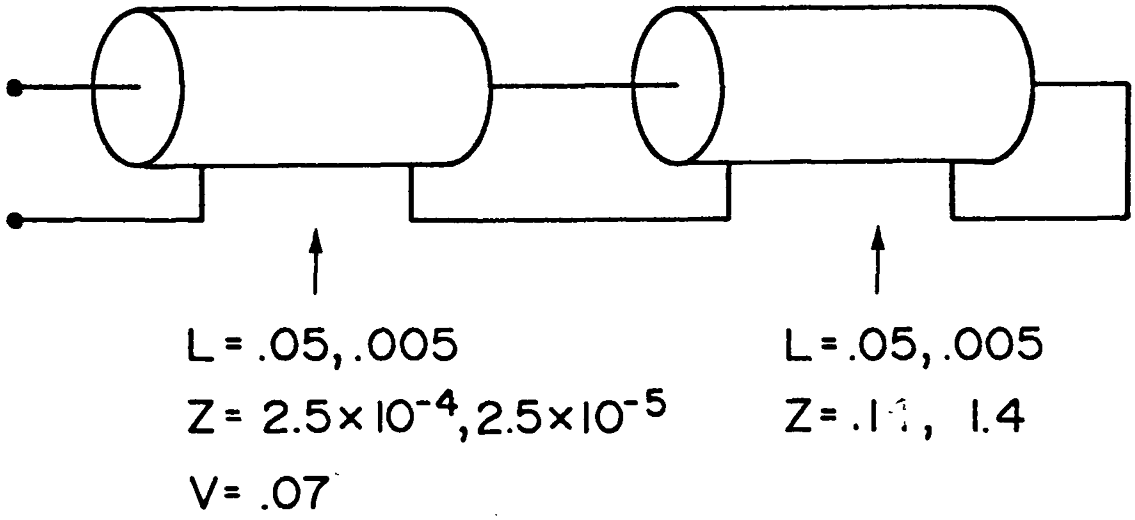



Fig. 13: (a) Imploding foil circuit (b) transmission line model.

```
3574 REM----IMPLODING FOIL SUBROUTINE
3575 REM----Y1=FOIL MASS IN G
3576 REM----Y2=CYLINDER HEIGHT IN CM
3577 REM----X1=CYLINDER RADIUS IN CM
3578 REM----X2=CYLINDER VELOCITY IN CM/US
3579 REM----X3=CYLINDER ACCELERATION IN CM/US↑2
3580 REM----X4=CURRENT IN MA
3581 Y1=0.02
3582 Y2=2
3583 IF T>1 THEN 3586
3584 X1=7
3585 X2=0
3586 X4=(-V1(N2)+V2(N2,T0))/O2
3587 X3=0.01/Y1*Y2*X4*X4/X1
3588 X2=X2+X3*T2
3589 X1=X1-X2*T2
3590 O2=O2+0.002*Y2*X2/X1/L(I)
3591 REM----FOIL RADIUS (LABELED "R")
3592 W(W3,T5)=X1
3593 REM----FOIL (MAG+KIN) ENERGY (LABELED "E")
3594 W(W3+1,T5)=0.5*O2*L(I)*T2*X4*X4+0.05*Y1*X2*X2
3595 IF T=1 THEN 3598
3596 REM----FLUX, CALC AS /VdT (LABELED "F")
3597 W(W3+2,T5)=(V1(N2)+V2(N2,T0))*T2+W(W3+2,T5-1)
3598 REM----FLUX, CALC AS L*I (LABELED"P")
3599 W(W3+3,T5)=L(I)*O2*X4*T2
3600 W3=W3+4
3601 REM-----END OF SUBROUTINE
```

Fig. 13c: The subroutine used to model the collapsing foil.

```
Enter the number of elements:  2
Enter total time, timestep, [starting time], [plotstep]:  1.6,.05
Enter the total number of plots desired:  6

Enter L, Z, [V0], [I0] for element 1 :  .05,2.5E-4,.07
Enter L, Z, [V0], [I0] for element 2 :  .05,.14V
Enter the name of the variable impedance subroutine:  IMPLFL

Enter the junction type for junction 1 :  1
Enter the end number and resistance:  1,1E6
Enter the junction type for junction 2 :  2
Enter the end numbers:  2,3
Enter the junction type for junction 3 :  1
Enter the end number and resistance:  4,0

Enter the end number and V, I, P, E or Z for plot 1:  4,I
Enter the end number and V, I, P, E or Z for plot 2:  3,E
Enter the end number and V, I, P, E or Z for plot 3:  0,R
Enter the end number and V, I, P, E or Z for plot 4:  0,E
Enter the end number and V, I, P, E or Z for plot 5:  0,F
Enter the end number and V, I, P, E or Z for plot 6:  0,P
```

Fig. 13d: Input and output for a run with 30 timesteps to foil collapse ("R", "E", "F" and "P" are defined in the subroutine).

```
BERTHA :- NRL GAMBLE GROUP TRANSMISSION LINE CODE   CONFIGURATION LISTING

CONFIG. NAME: E4        17-JUN-83 14:59:52

QUANTITY                          VARIABLE NAME              VALUE
Number of elements                      N                     2
Total time                              T1                    1.600
Timestep                                T2                    0.050
Waveform start time                     T3                    0.000
Waveform plot step                      T4                    1
Number of plots                         W0                    6
Number of input pulses                  P0                    0
Number of var impedances                O0                    1
Number of var loads                     R0                    0
Number of switches                      S0                    0

ELEMENT NO        L            Z            V0           I0
    1         5.00E-002    2.50E-004    7.00E-002    0.00E+000
    2         5.00E-002    1.40E-001    0.00E+000    0.00E+000

JUNC #     J(I,1) TYPE    J(I,2) QUANT     J(I,3) QUANT     J(I,4) QUANT
    1        1  Resist      1  End Num      0  -------  1.00E+006 Resist
    2        2  Simple      2  End Num      3  End Num        0   -------
    3        1  Resist      4  End Num      0  -------  0.00E+000 Resist

INPUT PULSE  END        VAR IMPEDANCE  ELT        VAR RESISTANCE  END
  000000      0            IMPLFL       2             000000       0

PLOT LISTING       END  NUMBER      TYPE
Plot No.:  1              4        Current
Plot No.:  2              3        Energy
Plot No.:  3              0           R
Plot No.:  4              0           E
Plot No.:  5              0           F
Plot No.:  6              0           P
```

Fig. 13d (Cont'd): Input and output for a run with 30 timesteps to foil collapse ("R", "E", "F" and "P" are defined in the subroutine).

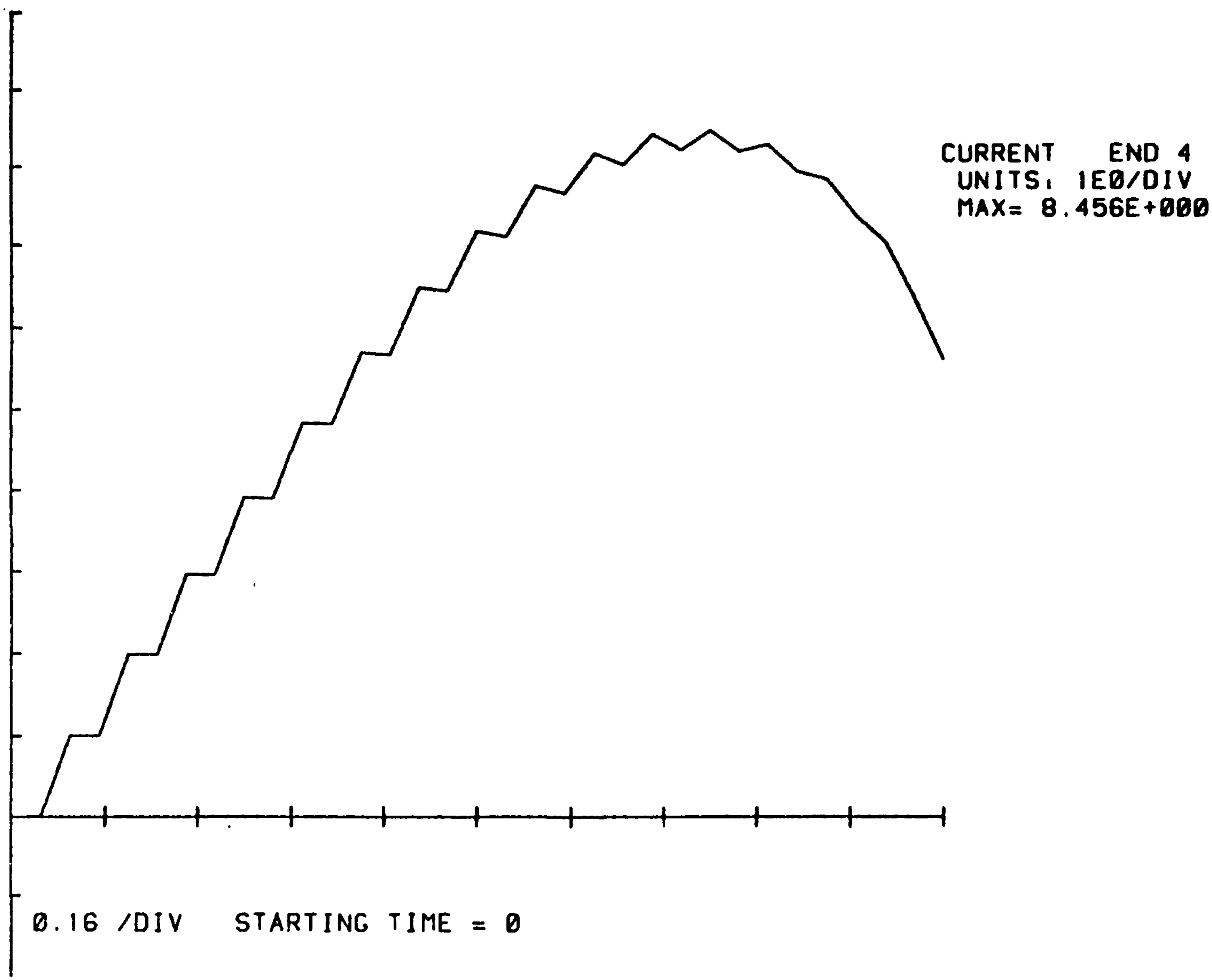



Fig. 13d (Cont'd): Input and output for a run with 30 timesteps to foil collapse ("R", "E", "F" and "P" are defined in the subroutine).

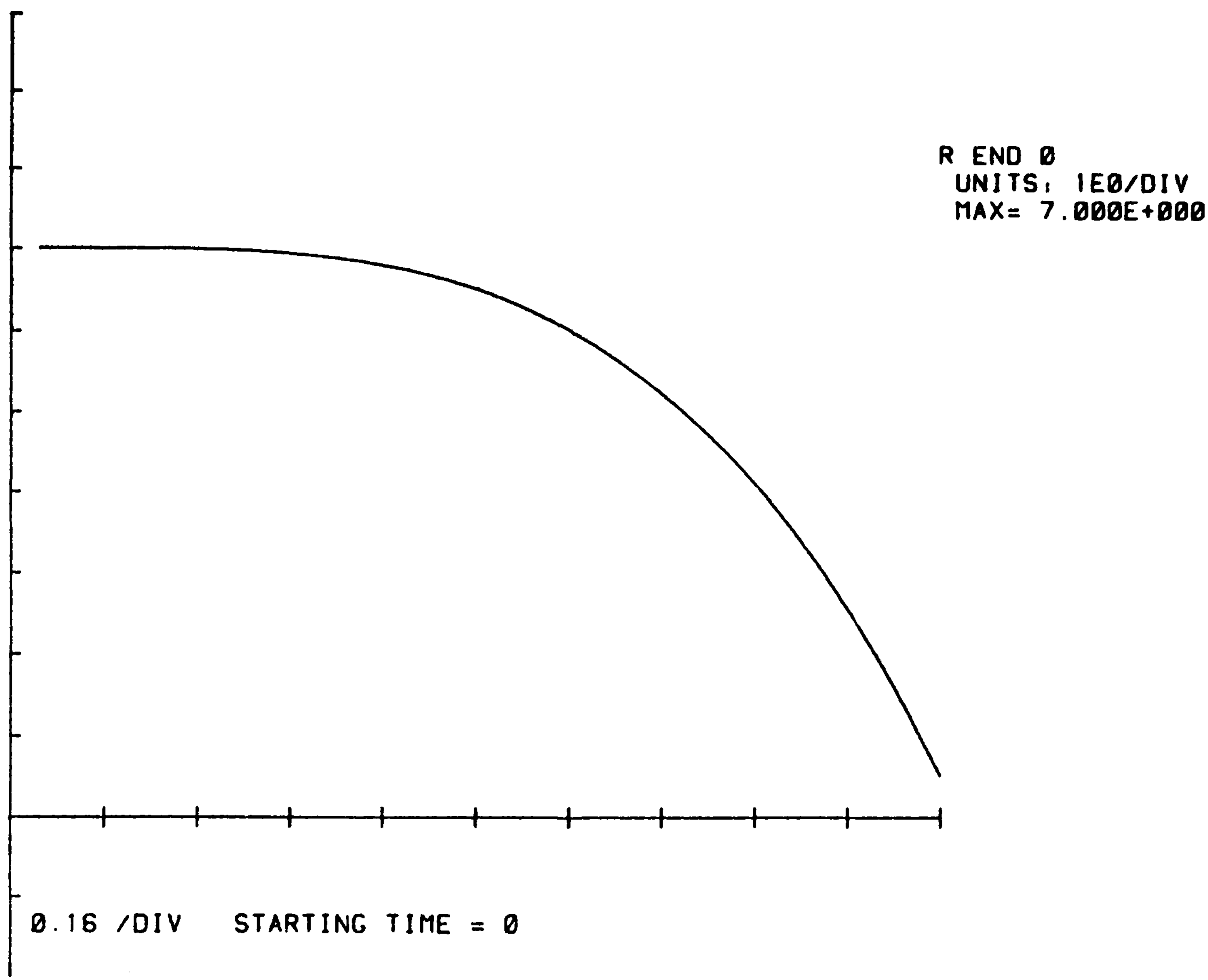



Fig. 13d (Cont'd): Input and output for a run with 30 timesteps to foil collapse ("R", "E", "F" and "P" are defined in the subroutine).

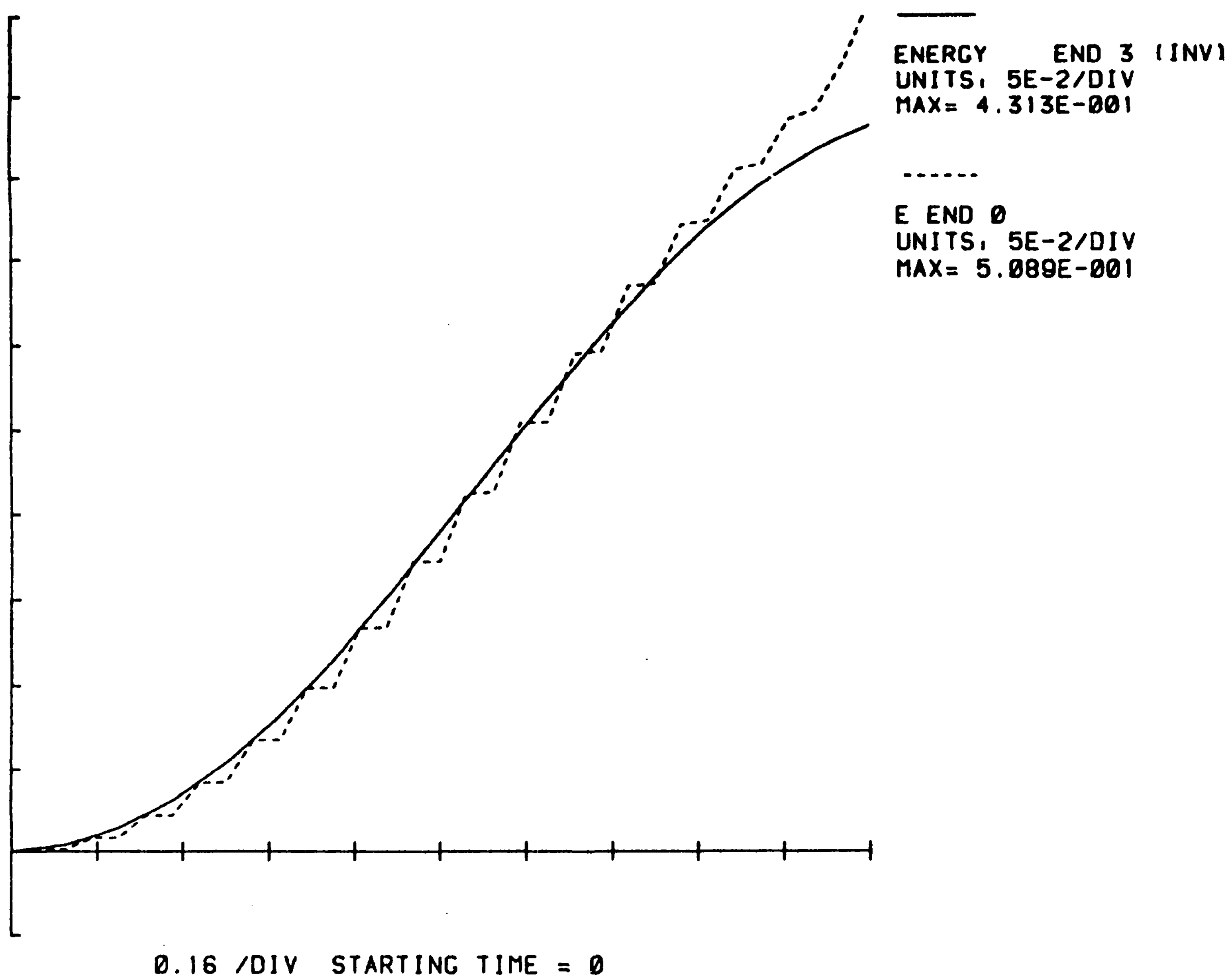



Fig. 13d (Cont'd): Input and output for a run with 30 timesteps to foil collapse ("R", "E", "F" and "P" are defined in the subroutine).

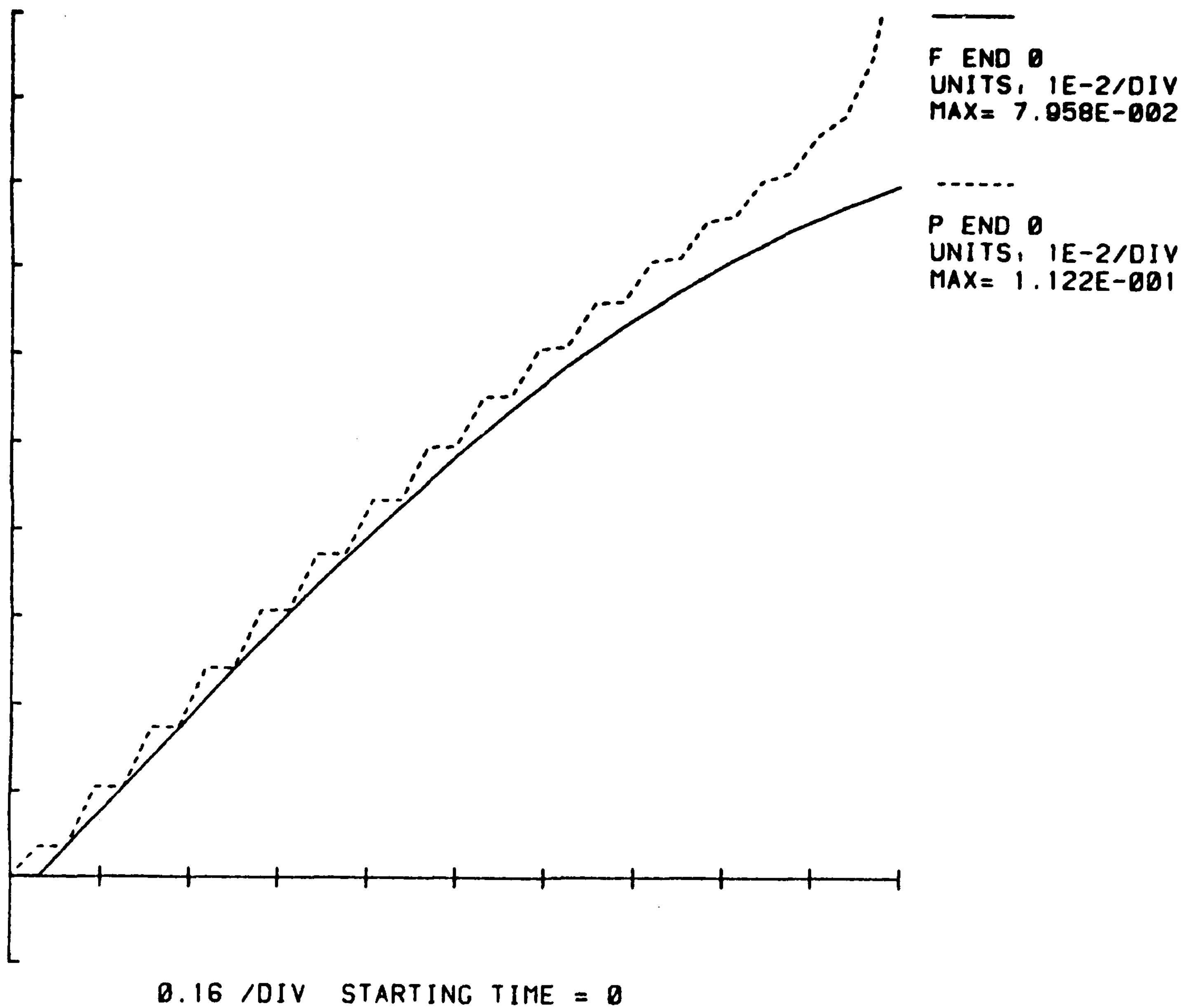



Fig. 13d (Cont'd): Input and output for a run with 30 timesteps to foil collapse ("R", "E", "F" and "P" are defined in the subroutine).

```
Enter the number of elements:  2
Enter total time, timestep, [starting time], [plotstep]:  1.6,.005
Enter the total number of plots desired:  6

Enter L, Z, [V0], [I0] for element 1 :  .005,2.5E-5,.07
Enter L, Z, [V0], [I0] for element 2 :  .005,1.4V
Enter the name of the variable impedance subroutine:  IMPLFL

Enter the junction type for junction 1 :  1
Enter the end number and resistance:  1,1E6
Enter the junction type for junction 2 :  2
Enter the end numbers:  2,3
Enter the junction type for junction 3 :  1
Enter the end number and resistance:  4,0

Enter the end number and V, I, P, E or Z for plot 1:  4,I
Enter the end number and V, I, P, E or Z for plot 2:  3,E
Enter the end number and V, I, P, E or Z for plot 3:  0,R
Enter the end number and V, I, P, E or Z for plot 4:  0,E
Enter the end number and V, I, P, E or Z for plot 5:  0,F
Enter the end number and V, I, P, E or Z for plot 6:  0,P
```

Fig. 13e: Input and output for a similar run but with 300 timesteps to foil collapse.

```
BERTHA - NRL GAMBLE GROUP TRANSMISSION LINE CODE   CONFIGURATION LISTING

CONFIG. NAME: E4A       17-JUN-83 15:20:55

QUANTITY                         VARIABLE NAME          VALUE
Number of elements                     N                  2
Total time                             T1                 1.600
Timestep                               T2                 0.005
Waveform start time                    T3                 0.000
Waveform plot step                     T4                 1
Number of plots                        W0                 6
Number of input pulses                 P0                 0
Number of var impedances               O0                 1
Number of var loads                    R0                 0
Number of switches                     S0                 0

ELEMENT NO         L              Z            V0            I0
    1          5.00E-003      2.50E-005    7.00E-002     0.00E+000
    2          5.00E-003      1.40E+000    0.00E+000     0.00E+000

JUNC #     J(I,1) TYPE     J(I,2) QUANT     J(I,3) QUANT       J(I,4) QUANT
   1         1 Resist        1 End Num        0 -------  1.00E+006 Resist
   2         2 Simple        2 End Num        3 End Num       0  -------
   3         1 Resist        4 End Num        0 -------  0.00E+000 Resist

INPUT PULSE  END         VAR IMPEDANCE  ELT        VAR RESISTANCE  END
  000000      0              IMPLFL      2             000000       0

PLOT LISTING       END  NUMBER      TYPE
Plot No.:  1             4         Current
Plot No.:  2             3         Energy
Plot No.:  3             0            R
Plot No.:  4             0            E
Plot No.:  5             0            F
Plot No.:  6             0            P
```

Fig. 13e (Cont'd): Input and output for a similar run but with 300 timesteps to foil collapse.

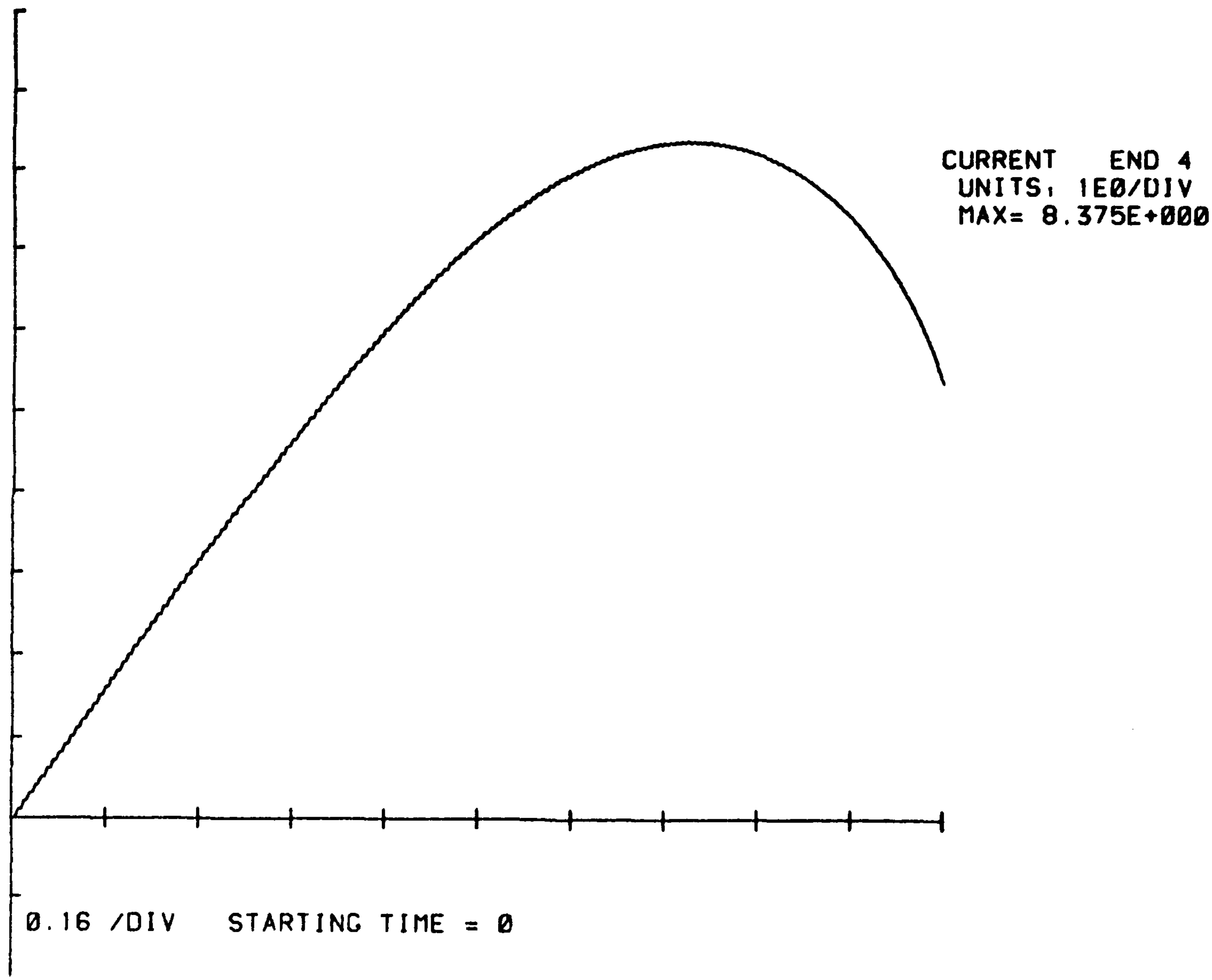



Fig. 13e (Cont'd): Input and output for a similar run but with 300 timesteps to foil collapse.

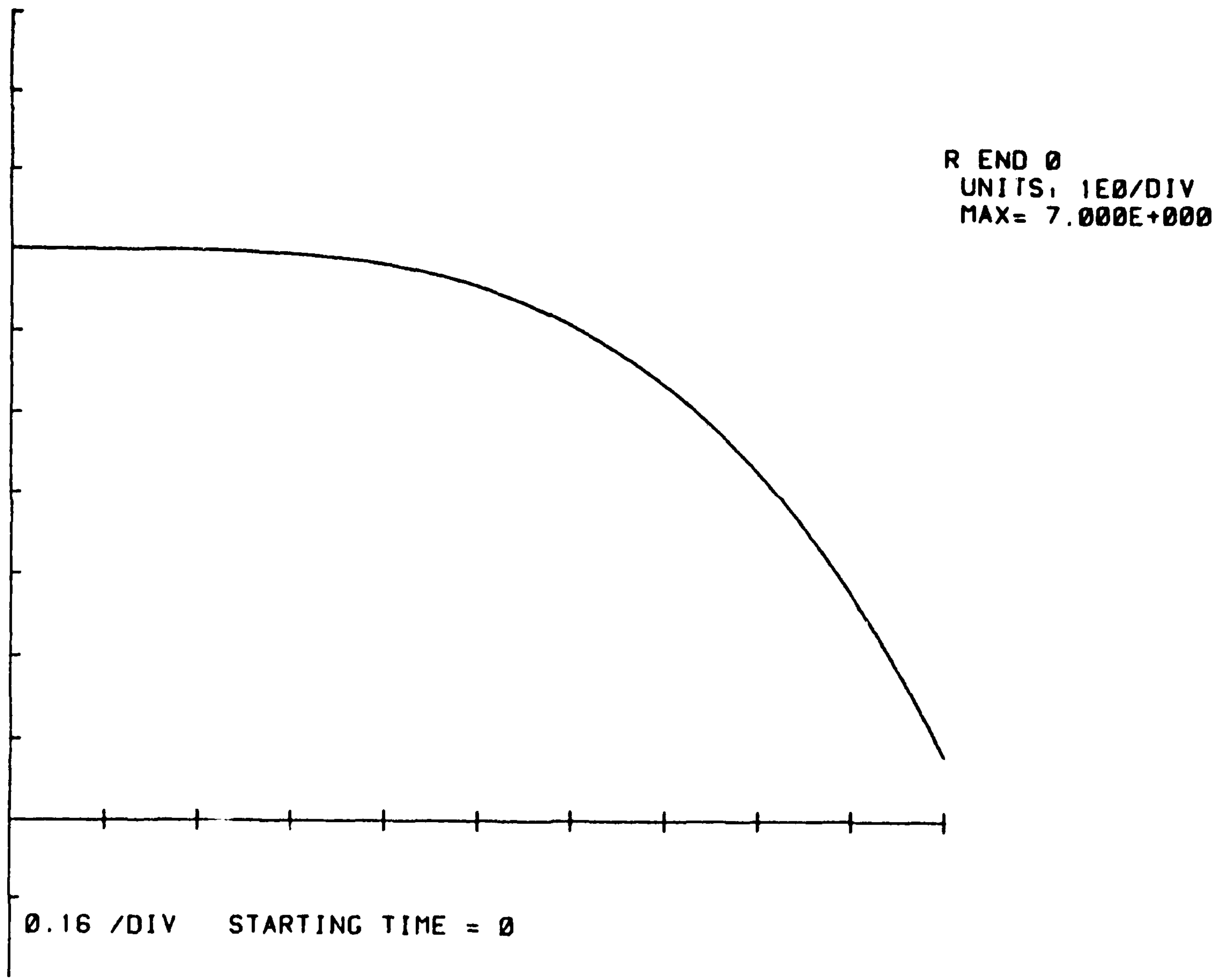



Fig. 13e (Cont'd): Input and output for a similar run but with 300 timesteps to foil collapse.

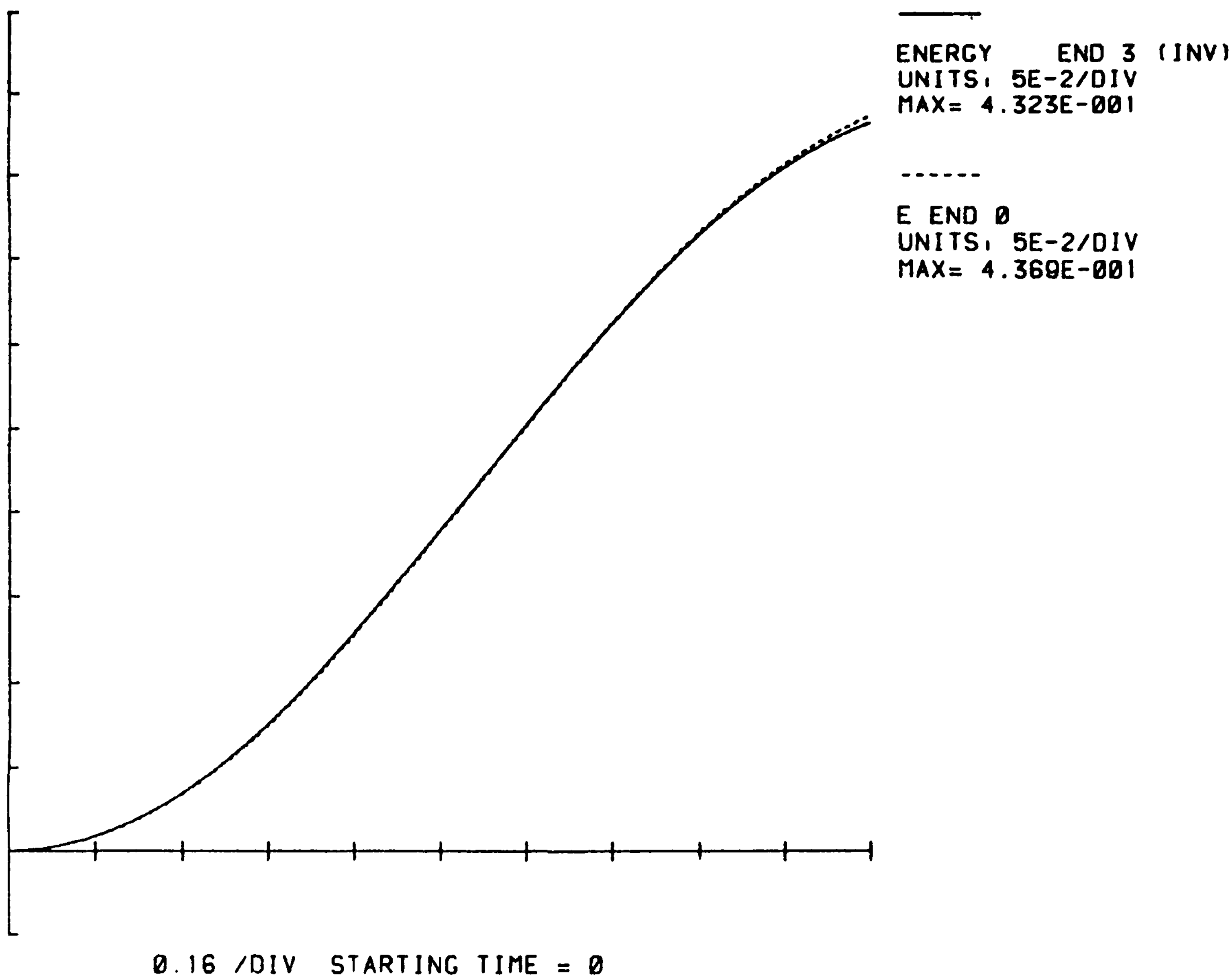



Fig. 13e (Cont'd): Input and output for a similar run but with 300 timesteps to foil collapse.

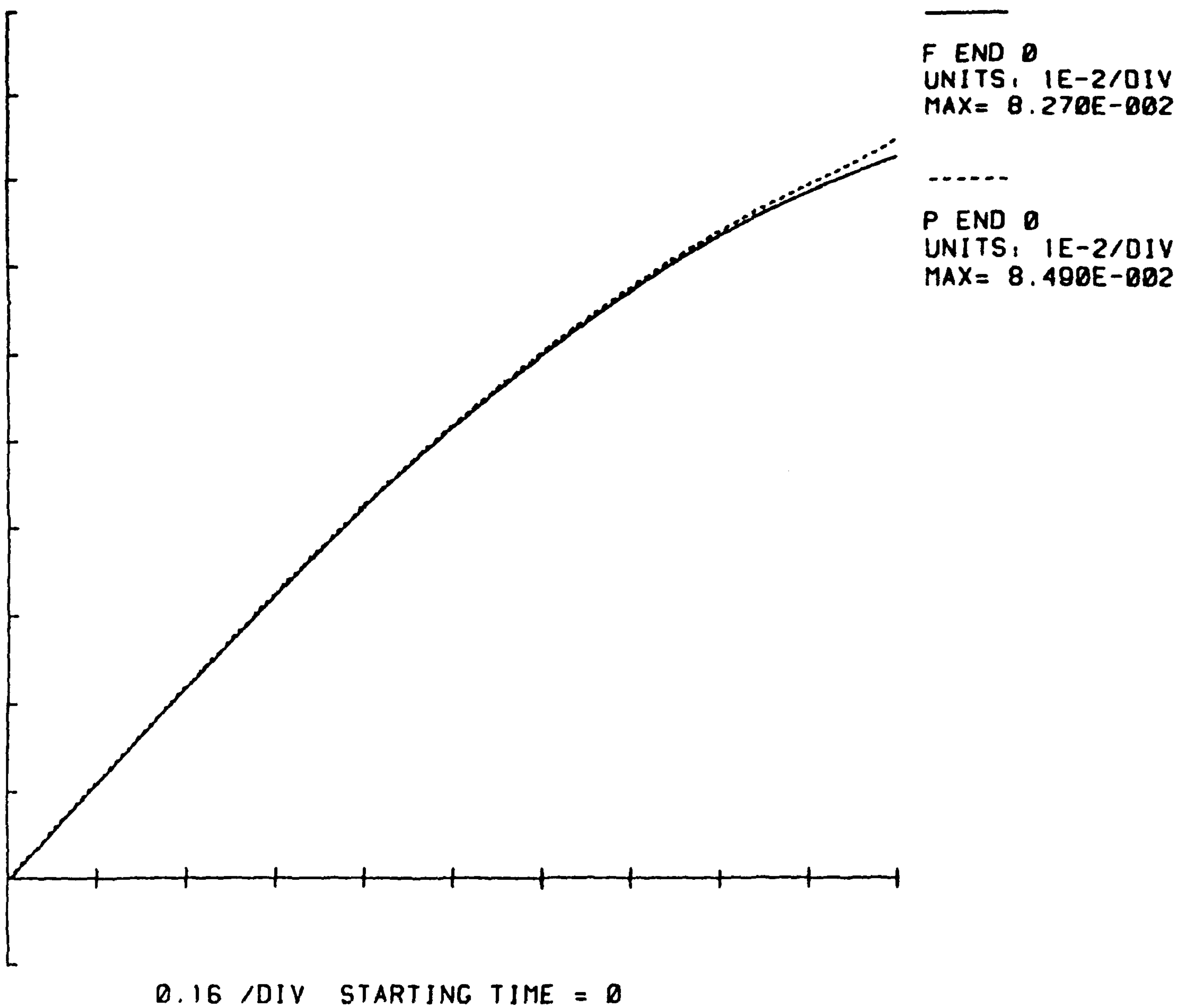



Fig. 13e (Cont'd): Input and output for a similar run but with 300 timesteps to foil collapse.

# LIMITATIONS

An idealized transmission line element is one dimensional, supporting only TEM waves. Errors may result when this code is used to model two dimensional structures, such as that shown in Fig. 14a, as the solutions to these problems will in general involve higher order TE and/or TM modes. Often these two dimensional effects may be simulated by a clever choice of the transmission line element configuration. For example, in Ref 6 it is shown that the structure in Fig 14a can be approximated by two shunt capacitors as shown in Figs. 14b and 14c.

The finite difference nature of this program can cause errors when the values of resistors and element impedances are functions of the electrical quantities. These errors may be in the form of a calculated solution that diverges from the correct solution, or in the form of large numerical instabilities. The imploding foil in the previous section is an example of the former, while the latter problem can occur, for example, in magnetically insulated transmission line simulations. A situation can arise where the shunt current across a line that is not insulated at a given timestep will load down the line voltage on the next timestep to the point where the line becomes insulated, thus shorting off the shunt current, which will raise the line voltage back up on the succeeding timestep, and so on. This problem has been remedied in practice[7] by iterating within the shunt resistance subroutine to find a self-consistent shunt resistance. In general, when resistances or element impedances are varied, it is a good idea to check that the calculated solution does not change greatly when the run is repeated with a smaller timestep.

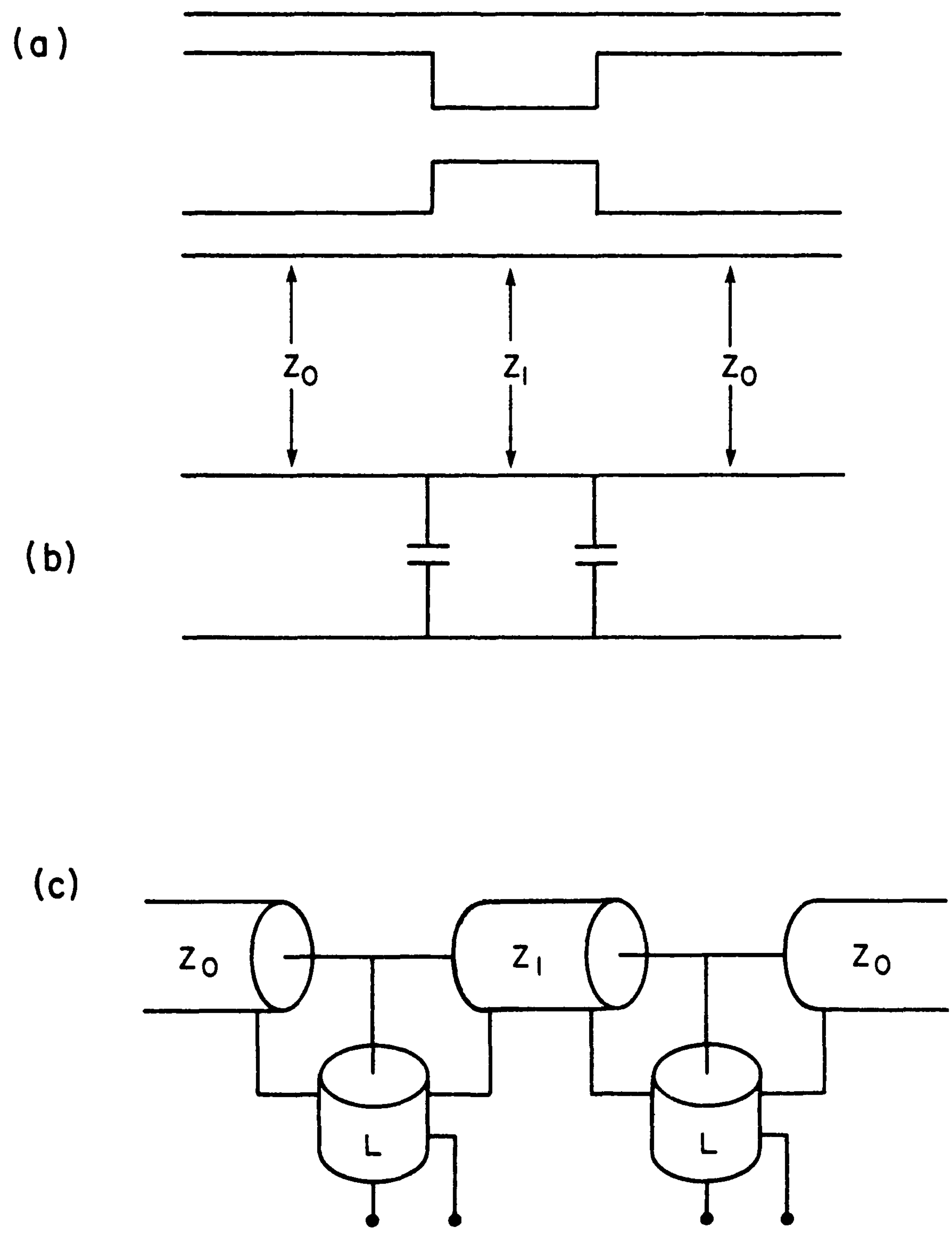



Fig. 14: A two dimensional structure (a) is modeled with shunt capacitors (b); transmission line representation (c).

## SUMMARY

This program is quite powerful, permitting the simulation of a wide variey of systems subject to the limitations described above. It is easy to use and readily implemented on a small microcomputer.

## ACKNOWLEDGMENTS

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## APPENDIX A - JUNCTION SCATTERING COEFFICIENTS

Again, the incident and reflected waves at an element end are related to the standing wave voltage and current according to:

$$2\,V_I = V + IZ \tag{A-1a}$$

$$V_R = V - V_I \tag{A-1b}$$

For the parallel tee (see Fig. 5):

$$V_1 = V_2 = V_3 \equiv V \tag{A-2a}$$

$$I_1 + I_2 + I_3 = 0 \tag{A-2b}$$

Writing Eq. A-1a for each element end, adding the resulting equations and using Eq. A-2a and Eq. A-2b gives:

$$V = \frac{\dfrac{2V_{1I}}{Z_1} + \dfrac{2V_{2I}}{Z_2} + \dfrac{2V_{3I}}{Z_3}}{1/Z_1 + 1/Z_2 + 1/Z_3}$$

Combining this with Eq. A-1b then gives:

$$V_{1R} = V_{1I}(2K_1-1) + V_{2I}(2K_2) + V_{3I}(2K_3)$$

$$V_{2R} = V_{1I}(2K_1) + V_{2I}(2K_2-1) + V_{3I}(2K_3)$$

$$V_{3R} = V_{1I}(2K_1) + V_{2I}(2K_2) + V_{3I}(2K_3-1)$$

where

$$K_1 = \frac{1/Z_1}{1/Z_1 + 1/Z_2 + 1/Z_3}$$

$$K_2 = \frac{1/Z_2}{1/Z_1 + 1/Z_2 + 1/Z_3}$$

$$K_3 = \frac{1/Z_3}{1/Z_1 + 1/Z_2 + 1/Z_3}$$

For the series tee (see Fig. 5) (noting that the junction is not symmetric):

$$-I_1 = I_2 = I_3 \equiv I \qquad \text{(A-3a)}$$

$$V_1 - V_2 - V_3 = 0 \qquad \text{(A-3b)}$$

Again, writing Eq. A-1a for each element end, adding the resulting equations and using Eq. A-3a and Eq. A-3b gives:

$$I = \frac{-2V_{1I} + 2V_{2I} + 2V_{3I}}{Z_1 + Z_2 + Z_3}$$

And once more using Eq. A-1b gives:

$$V_{1R} = V_{1I}\,(1-2K_1) + V_{2I}(2K_1) + V_{3I}(2K_1)$$

$$V_{2R} = V_{1I}(2K_2) + V_{2I}(1-2K_2) - V_{3I}(2K_2)$$

$$V_{3R} = V_{1I}(2K_3) - V_{2I}(2K_3) + V_{3I}(1-2K_3)$$

where

$$K_1 = \frac{Z_1}{Z_1 + Z_2 + Z_3}$$

$$K_2 = \frac{Z_2}{Z_1 + Z_2 + Z_3}$$

$$K_3 = \frac{Z_3}{Z_1 + Z_2 + Z_3}$$

The other junction types are all special cases of these two.

# APPENDIX B - SAMPLE PROGRAM

The following is a simplified version of BERTHA which illustrates most of the essential features of this program. Both this and the full program in App. C are written in BASIC for the Tektronix 4050 series microcomputers, although translation into other languages should be very straightforward.

```
100 REM ************ BERTHA - SAMPLE PROGRAM ***********
110 REM **** NAVAL RESEARCH LAB  WASHINGTON, D. C. ****
120 REM
130 REM
140 REM ---------- DATA ENTRY
150 REM
160 PRINT "Enter number of elements, total time and number of plots:  ";
170 INPUT N,T1,W0
180 DELETE L,Z,V0,I0,J,W1,M,V1,V2,W
190 DIM L(N),Z(N),V0(N),I0(N),J(N+1,4),W1(W0)
200 REM ---------Enter the element properties
210 PRINT
220 FOR I=1 TO N
230 PRINT "Enter L, Z, V0, I0 for element ";I;" :  ";
240 INPUT L(I),Z(I),V0(I),I0(I)
250 NEXT I
260 REM ---------Enter the junction properties
270 J=0
280 FOR I=1 TO N+1
290 PRINT "Enter the junction type for junction ";I;" :  ";
300 INPUT J(I,1)
310 GO TO J(I,1) OF 320,360,400,400,440,480
320 REM-------Type 1 junction (resistive termination)
330 PRINT "Enter the end number and resistance:  ";
340 INPUT J(I,2),J(I,4)
350 GO TO 510
360 REM-------Type 2 junction (simple junction)
370 PRINT "Enter the end numbers:  ";
380 INPUT J(I,2),J(I,3)
390 GO TO 510
400 REM-------Types 3 and 4 junctions (shunt and series resistances)
410 PRINT "Enter the end numbers and resistance:  ";
420 INPUT J(I,2),J(I,3),J(I,4)
430 GO TO 510
440 REM-------Type 5 junction (parallel tee)
450 PRINT "Enter the end numbers:  ";
460 INPUT J(I,2),J(I,3),J(I,4)
```

```
470 GO TO 510
480 REM-------Type 6 junction (series tee)
490 PRINT "Enter the end numbers in the order HHGG, GG, HH:  ";
500 INPUT J(I,2),J(I,3),J(I,4)
510 NEXT I
520 REM ---------Enter the plots desired
530 FOR I=1 TO W0
540 PRINT "Enter the end number for plot ";I;":  ";
550 INPUT W1(I)
560 NEXT I
570 REM
580 REM ---------- INITIALIZATION AND CONVERSION OF J TO M
590 REM
600 REM-------Initialization
610 L=L+0.1
620 REM-------(do this to avoid errors when rounding off)
630 L=INT(L)
640 CALL "MAX",L,L0,L9
650 REM-------(L0 is the maximum; L9 is a dummy variable)
660 DIM M(2*N,5),V1(2*N),V2(2*N,L0),W(W0,T1)
670 V1=0
680 V2=0
690 M=0
700 FOR I=1 TO 2*N
710 M(I,4)=1
720 M(I,5)=1
730 NEXT I
740 REM -------- Backfill V2 for initial voltage and current
750 FOR I=1 TO N
760 FOR I1=L0 TO L0-L(I)+1 STEP -1
770 V2(2*I,I1)=(V0(I)-I0(I)*Z(I))/2
780 V2(2*I-1,I1)=(V0(I)+I0(I)*Z(I))/2
790 NEXT I1
800 NEXT I
810 REM---------Calculate M from J
820 FOR I=1 TO N+1
830 N1=J(I,2)
```

```
840 Z1=Z(INT((N1+1)/2))
850 GO TO J(I,1) OF 860,900,900,900,900,900
860 REM --- Coeffs for type 1 junction (resistive termination)
870 R=J(I,4)
880 M(N1,1)=(R-Z1)/(R+Z1)
890 GO TO 1530
900 N2=J(I,3)
910 Z2=Z(INT((N2+1)/2))
920 M(N1,4)=N2
930 M(N2,4)=N1
940 GO TO J(I,1)-1 OF 950,1020,1110,1190,1190
950 REM --- Coefs for type 2 junction (simple junction)
960 K=(Z2-Z1)/(Z2+Z1)
970 M(N1,1)=K
980 M(N1,2)=1-K
990 M(N2,1)=-K
1000 M(N2,2)=K+1
1010 GO TO 1530
1020 REM --- Coeffs for type 3 junction (shunt resistance)
1030 R=J(I,4)
1040 K1=1/Z1/(1/Z1+1/Z2+1/R)
1050 K2=Z1/Z2*K1
1060 M(N1,1)=2*K1-1
1070 M(N1,2)=2*K2
1080 M(N2,1)=2*K2-1
1090 M(N2,2)=2*K1
1100 GO TO 1530
1110 REM --- Coeffs for type 4 junction (series resistance)
1120 R=J(I,4)
1130 K=1/(Z1+Z2+R)
1140 M(N1,1)=1-2*Z1*K
1150 M(N1,2)=2*Z1*K
1160 M(N2,1)=1-2*Z2*K
1170 M(N2,2)=2*Z2*K
1180 GO TO 1530
1190 N3=J(I,4)
```

```
1200 Z3=Z(INT((N3+1)/2))
1210 M(N1,5)=N3
1220 M(N2,5)=N3
1230 M(N3,4)=N1
1240 M(N3,5)=N2
1250 IF J(I,1)=6 THEN 1400
1260 REM --- Coeffs for type 5 junction (parallel tee)
1270 K1=1/Z1/(1/Z1+1/Z2+1/Z3)
1280 K2=Z1/Z2*K1
1290 K3=Z1/Z3*K1
1300 M(N1,1)=2*K1-1
1310 M(N1,2)=2*K2
1320 M(N1,3)=2*K3
1330 M(N2,1)=2*K2-1
1340 M(N2,2)=2*K1
1350 M(N2,3)=2*K3
1360 M(N3,1)=2*K3-1
1370 M(N3,2)=2*K1
1380 M(N3,3)=2*K2
1390 GO TO 1530
1400 REM --- Coeffs for type 6 junction (series tee)
1410 K1=Z1/(Z1+Z2+Z3)
1420 K2=Z2/Z1*K1
1430 K3=Z3/Z1*K1
1440 M(N1,1)=1-2*K1
1450 M(N1,2)=2*K1
1460 M(N1,3)=2*K1
1470 M(N2,1)=1-2*K2
1480 M(N2,2)=2*K2
1490 M(N2,3)=-2*K2
1500 M(N3,1)=1-2*K3
1510 M(N3,2)=2*K3
1520 M(N3,3)=-2*K3
1530 NEXT I
1540 REM
```

```
1550 REM -------- EXECUTION OF PROGRAM
1560 REM
1570 T0=1
1580 FOR T=1 TO T1
1590 REM --- Calculate incident waves from waves leaving opp ends
1600 FOR I=1 TO N
1610 V1(2*I)=V2(2*I-1,T0-L(I)+L0*(T0<=L(I)))
1620 V1(2*I-1)=V2(2*I,T0-L(I)+L0*(T0<=L(I)))
1630 NEXT I
1640 REM --- Calculate reflected waves from incident waves
1650 FOR I=1 TO 2*N
1660 V2(I,T0)=M(I,1)*V1(I)+M(I,2)*V1(M(I,4))+M(I,3)*V1(M(I,5))
1670 NEXT I
1680 REM --- Save voltages for plotting
1690 FOR I=1 TO W0
1700 W(I,T)=V1(W1(I))+V2(W1(I),T0)
1710 NEXT I
1720 T0=T0+1-L0*(T0+1>L0)
1730 NEXT T
```

## APPENDIX C - PROGRAM LISTING

The full BERTHA program, as it currently exists, is listed here. (The various routines are accessed by pressing the special function keys on the 4050 series machines). The start and execution routines together comprise an expanded version of the sample program in App. B. The remaining routines pertain to I/O and disk storage and, as they will be highly dependent on the requirements of the user, are listed here without comment (additional routines for waveform storage are omitted for clarity).

```
100 REM ---------------------------START ROUTINE----
110 PAGE
120 PRINT "BERTHA - TRANSMISSION LINE CODEJJJJJ"
130 DELETE L,Z,V0,I0,J,J1,W1,P1,P,O1,R1,C1,O9,J9
140 DELETE P$,O$,R$,A$,B$,C$
150 DIM B$(7),C$(18)
160 Z5=0
170 OPEN "$D/CONFIGS/CLIST";1,"R",Z$
180 READ #1:C1
190 DIM A$(C1)
200 READ #1:A$
210 CLOSE
220 PRINT "Enter the name of the desired configuration:  ";
230 INPUT B$
240 IF B$="" THEN 370
250 C$="0000000"
260 C$=REP(B$,1,LEN(B$))
270 IF POS(A$,C$,1)<>0 THEN 300
280 PRINT "Configuration does not exist - try again"
290 GO TO 220
300 C$="$D/CONFIGS/"&C$
310 OPEN C$;1,"R",Z$
320 READ #1:Y1,N,T1,T2,T3,T4,W0,Z5,P0,O0,R0,S0,J0
330 DIM L(N),Z(N),V0(N),I0(N),J(N+1,4),J1(J0),W1(W0,2),P1(9),O1(9),R1(9)
340 READ #1:L,Z,V0,I0,J,J1,W1,P1,P$,O1,O$,R1,R$
350 CLOSE
360 GO TO 1870
370 REM --------------------Data Entry-----
380 PAGE
390 PRINT "Enter the number of elements:  ";
400 INPUT N
410 T3=0
420 T4=1
430 PRINT "Enter total time, timestep, [starting time], [plotstep]:  ";
440 INPUT T1,I$
450 T2=VAL(I$)
460 I1=POS(I$,",",2)
```

```
470 IF I1=Ø THEN 540
480 I$=REP("",1,I1)
490 T3=VAL(I$)
500 I1=POS(I$,",",1)
510 IF I1=Ø THEN 540
520 I$=REP("",1,I1)
530 T4=VAL(I$)
540 PRINT "Enter the total number of plots desired:  ";
550 INPUT WØ
560 DIM L(N),Z(N),VØ(N),IØ(N),J(N+1,4),W1(WØ,2)
570 DIM P1(9),O1(9),R1(9),O9(N),J9(N+1)
580 O9=Ø
590 J9=Ø
600 VØ=Ø
610 IØ=Ø
620 P$="ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-"
630 PØ=Ø
640 P1=Ø
650 O$="ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-"
660 OØ=Ø
670 O1=Ø
680 R$="ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-ØØØØØØ-"
690 RØ=Ø
700 R1=Ø
710 SØ=Ø
720 J=Ø
730 REM ---------Enter the element properties
740 PRINT
750 FOR I=1 TO N
760 PRINT "Enter L, Z, [VØ], [IØ] for element ";I;" :  ";
770 INPUT L(I),I$
780 Z(I)=VAL(I$)
790 IF POS(I$,"V",1)=Ø THEN 860
800 O9(I)=1
810 PRINT "Enter the name of the variable impedance subroutine:  ";
820 INPUT O$
830 OØ=OØ+1
```

```
840 O$=REP(O$,(O0-1)*7+1,LEN(O$))
850 O1(O0)=I
860 I1=POS(I$,",",2)
870 IF I1=0 THEN 940
880 I$=REP("",1,I1)
890 V0(I)=VAL(I$)
900 I1=POS(I$,",",1)
910 IF I1=0 THEN 940
920 I$=REP("",1,I1)
930 I0(I)=VAL(I$)
940 NEXT I
950 REM ---------Enter the junction properties
960 PRINT
970 FOR I=1 TO N+1
980 PRINT "Enter the junction type for junction ";I;" :  ";
990 INPUT J(I,1)
1000 GO TO J(I,1) OF 1010,1180,1340,1340,1450,1480,1520,1520,1560,1210
1010 PRINT "Enter the end number and resistance:  ";
1020 INPUT J(I,2),I$
1030 J(I,4)=VAL(I$)
1040 IF POS(I$,"V",1)=0 THEN 1110
1050 R0=R0+1
1060 PRINT "Enter the name of the variable resistance subroutine:  ";
1070 INPUT O$
1080 R$=REP(O$,(R0-1)*7+1,LEN(O$))
1090 R1(R0)=I
1100 J9(I)=1
1110 IF POS(I$,"I",1)=0 THEN 1170
1120 P0=P0+1
1130 PRINT "Enter the name of the input pulse:  ";
1140 INPUT O$
1150 P$=REP(O$,(P0-1)*7+1,LEN(O$))
1160 P1(P0)=I
1170 GO TO 1620
1180 PRINT "Enter the end numbers:  ";
1190 INPUT J(I,2),J(I,3)
```

```
1200 GO TO 1610
1210 REM-----Type 10 junction - type 2 fill
1220 PRINT "Enter the initial and final end numbers for type 2 fill:  ";
1230 INPUT J7,J8
1240 FOR I1=J7 TO J8-1 STEP 2
1250 J(I,1)=2
1260 J(I,2)=I1
1270 J(I,3)=I1+1
1280 IF O9(INT(I1+1)/2)+O9(INT(I1+2)/2)=0 THEN 1300
1290 J9(I)=1
1300 I=I+1
1310 NEXT I1
1320 I=I-1
1330 GO TO 1640
1340 PRINT "Enter the end numbers and resistance:  ";
1350 INPUT J(I,2),J(I,3),I$
1360 J(I,4)=VAL(I$)
1370 IF POS(I$,"V",1)=0 THEN 1440
1380 R0=R0+1
1390 PRINT "Enter the name of the variable resistance subroutine:  ";
1400 INPUT O$
1410 R$=REP(O$,(R0-1)*7+1,LEN(O$))
1420 R1(R0)=I
1430 J9(I)=1
1440 GO TO 1610
1450 PRINT "Enter the end numbers:  ";
1460 INPUT J(I,2),J(I,3),J(I,4)
1470 GO TO 1600
1480 PRI "Enter the end numbers in the order HHGG, GG, HH (see instr)";
1490 PRINT " :  ";
1500 INPUT J(I,2),J(I,3),J(I,4)
1510 GO TO 1600
1520 PRINT "Enter the end number and switching time:  ";
1530 INPUT J(I,2),J(I,3)
1540 S0=S0+1
1550 GO TO 1640
```

```
1560 PRINT "Enter the end number and breakdown voltage:   ";
1570 INPUT J(I,2),J(I,3)
1580 S0=S0+1
1590 GO TO 1620
1600 IF O9(INT((J(I,4)+1)/2))=1 THEN 1630
1610 IF O9(INT((J(I,3)+1)/2))=1 THEN 1630
1620 IF O9(INT((J(I,2)+1)/2))=0 THEN 1640
1630 J9(I)=1
1640 NEXT I
1650 REM --------Determine array J1 from array J9
1660 DIM J1(SUM(J9)+1)
1670 J0=1
1680 J1=0
1690 FOR I=1 TO N+1
1700 IF J9(I)=0 THEN 1730
1710 J0=J0+1
1720 J1(J0)=I
1730 NEXT I
1740 DELETE O9,J9
1750 REM --------Enter the plots desired
1760 PRINT
1770 FOR I=1 TO W0
1780 PRINT "Enter the end number and V, I, P, E or Z for plot ";I;":  ";
1790 INPUT W1(I,1),Z$
1800 W1(I,2)=(Z$=",V")+2*(Z$=",I")+3*(Z$=",Z")+4*(Z$=",P")+5*(Z$=",E")
1810 Z$=SEG(Z$,LEN(Z$),1)
1820 W1(I,2)=W1(I,2)*(W1(I,1)>0)+(W1(I,1)=0)*ASC(Z$)
1830 IF W1(I,2)<>3 THEN 1860
1840 PRINT "----Enter max. Impedance for plot:";
1850 INPUT Z5
1860 NEXT I
```

```
100 REM--------MAIN PROGRAM EXECUTION ROUTINE
110 REM-------Initialization
120 REM-------Express lengths and times in units of the timestep
130 T1=T1/T2+0.5
140 T1=INT(T1)
150 T3=T3/T2+0.5
160 T3=INT(T3)
170 L=L/T2
180 L=L+0.5
190 L=INT(L)
200 CALL "MAX",L,L0,L9
210 DELETE M,V1,V2,W,P,S
220 DIM M(2*N,5),V1(2*N),V2(2*N,L0)
230 DIM W(W0,INT((T1-T3)/T4+0.01))
240 IF P0=0 THEN 260
250 DIM P(P0,T1)
260 IF S0=0 THEN 290
270 DIM S(S0,3)
280 S0=0
290 M=0
300 FOR I=1 TO 2*N
310 M(I,4)=1
320 M(I,5)=1
330 NEXT I
340 V1=0
350 V2=0
360 W=0
370 REM----- Set initial V, I
380 FOR I=1 TO N
390 FOR I1=L0 TO L0-L(I)+1 STEP -1
400 V2(2*I,I1)=(V0(I)-I0(I)*Z(I))/2
410 V2(2*I-1,I1)=(V0(I)+I0(I)*Z(I))/2
420 NEXT I1
430 NEXT I
440 REM---------Calculate M
450 FOR I=1 TO N+1
460 IF J(I,1)=0 THEN 480
```

```
470 GOSUB 500
480 NEXT I
490 GO TO 1270
500 REM-------Subroutine for calculating array M from array J
510 N1=J(I,2)
520 Z1=Z(INT((N1+1)/2))
530 GO TO J(I,1) OF 590,630,630,630,630,630,540,540,540
540 S0=S0+1
550 S(S0,1)=J(I,2)
560 S(S0,2)=J(I,1)<9
570 S(S0,3)=J(I,3)
580 J(I,4)=1000000*(J(I,1)>7)
590 REM-------Coeffs for type 1 junction and switches
600 R=J(I,4)
610 M(N1,1)=(R-Z1)/(R+Z1)
620 GO TO 1260
630 N2=J(I,3)
640 Z2=Z(INT((N2+1)/2))
650 M(N1,4)=N2
660 M(N2,4)=N1
670 GO TO J(I,1)-1 OF 680,750,840,920,920
680 REM-------Coeffs for type 2 junction
690 K=(Z2-Z1)/(Z2+Z1)
700 M(N1,1)=K
710 M(N1,2)=1-K
720 M(N2,1)=-K
730 M(N2,2)=K+1
740 GO TO 1260
750 REM-------Coeffs for type 3 junction
760 R=J(I,4)
770 K1=1/Z1/(1/Z1+1/Z2+1/R)
780 K2=Z1/Z2*K1
790 M(N1,1)=2*K1-1
800 M(N1,2)=2*K2
810 M(N2,1)=2*K2-1
820 M(N2,2)=2*K1
```

```
830 GO TO 1260
840 REM-------Coeffs for type 4 junction
850 R=J(I,4)
860 K=1/(Z1+Z2+R)
870 M(N1,1)=1-2*Z1*K
880 M(N1,2)=2*Z1*K
890 M(N2,1)=1-2*Z2*K
900 M(N2,2)=2*Z2*K
910 GO TO 1260
920 N3=J(I,4)
930 Z3=Z(INT((N3+1)/2))
940 M(N1,5)=N3
950 M(N2,5)=N3
960 M(N3,4)=N1
970 M(N3,5)=N2
980 IF J(I,1)=6 THEN 1130
990 REM-------Coeffs for type 5 junction
1000 K1=1/Z1/(1/Z1+1/Z2+1/Z3)
1010 K2=Z1/Z2*K1
1020 K3=Z1/Z3*K1
1030 M(N1,1)=2*K1-1
1040 M(N1,2)=2*K2
1050 M(N1,3)=2*K3
1060 M(N2,1)=2*K2-1
1070 M(N2,2)=2*K1
1080 M(N2,3)=2*K3
1090 M(N3,1)=2*K3-1
1100 M(N3,2)=2*K1
1110 M(N3,3)=2*K2
1120 GO TO 1260
1130 REM-------Coeffs for type 6 junction
1140 K1=Z1/(Z1+Z2+Z3)
1150 K2=Z2/Z1*K1
1160 K3=Z3/Z1*K1
1170 M(N1,1)=1-2*K1
1180 M(N1,2)=2*K1
```

```
1190 M(N1,3)=2*K1
1200 M(N2,1)=1-2*K2
1210 M(N2,2)=2*K2
1220 M(N2,3)=-2*K2
1230 M(N3,1)=1-2*K3
1240 M(N3,2)=2*K3
1250 M(N3,3)=-2*K3
1260 RETURN
1270 REM---- Pull in input pulses
1280 IF P0=0 THEN 1420
1290 DELETE P2
1300 DIM P2(T1)
1310 FOR I=1 TO P0
1320 O$=SEG(P$,(I-1)*7+1,6)
1330 O$="$D/WAVEFORMS/"&O$
1340 OPEN O$;1,"R",Z$
1350 READ #1:P2
1360 CLOSE
1370 FOR I1=1 TO T1
1380 P(I,I1)=P2(I1)
1390 NEXT I1
1400 NEXT I
1410 DELETE P2
1420 REM-------Delete any external subroutines from previous runs
1430 DELETE 3481,10000
1440 REM-------Pull in the target lines for the external subroutines
1450 APPEND "@SYSLIB/BERTHA/APPEND";3480,50
1460 REM ----- Pull in var Imped subroutines
1470 IF O0=0 THEN 1710
1480 FOR I=1 TO O0
1490 O$=SEG(O$,(I-1)*7+1,6)
1500 O$="@SYSLIB/"&O$
1510 Z1=MEMORY
1520 GO TO I OF 1530,1550,1570,1590,1610,1630,1650,1670,1690
1530 APPEND O$;3730,1
1540 GO TO 1700
```

```
1550 APPEND O$;3830,1
1560 GO TO 1700
1570 APPEND O$;3930,1
1580 GO TO 1700
1590 APPEND O$;4030,1
1600 GO TO 1700
1610 APPEND O$;4130,1
1620 GO TO 1700
1630 APPEND O$;4230,1
1640 GO TO 1700
1650 APPEND O$;4330,1
1660 GO TO 1700
1670 APPEND O$;4430,1
1680 GO TO 1700
1690 APPEND O$;4530,1
1700 NEXT I
1710 REM ----- Pull in var resistance subroutines
1720 IF R0=0 THEN 1970
1730 T=0
1740 FOR I=1 TO R0
1750 O$=SEG(R$,(I-1)*7+1,6)
1760 Z$=SEG(O$,1,5)
1770 O$="@SYSLIB/"&O$
1780 GO TO I OF 1790,1810,1830,1850,1870,1890,1910,1930,1950
1790 APPEND O$;4630,1
1800 GO TO 1960
1810 APPEND O$;4730,1
1820 GO TO 1960
1830 APPEND O$;4830,1
1840 GO TO 1960
1850 APPEND O$;4930,1
1860 GO TO 1960
1870 APPEND O$;5030,1
1880 GO TO 1960
1890 APPEND O$;5130,1
1900 GO TO 1960
```

```
1910 APPEND O$;5230,1
1920 GO TO 1960
1930 APPEND O$;5330,1
1940 GO TO 1960
1950 APPEND O$;5430,1
1960 NEXT I
1970 REM-------Execution of program
1980 PAGE
1990 T0=1
2000 T5=0
2010 FOR T=1 TO T1
2020 REM-------Calculate incident waves from waves leaving opp ends
2030 FOR I=1 TO N
2040 V1(2*I)=V2(2*I-1,T0-L(I)+L0*(T0<=L(I)))
2050 V1(2*I-1)=V2(2*I,T0-L(I)+L0*(T0<=L(I)))
2060 NEXT I
2070 REM-------Calculate reflected waves from incident waves
2080 FOR I=1 TO 2*N
2090 V2(I,T0)=M(I,1)*V1(I)+M(I,2)*V1(M(I,4))+M(I,3)*V1(M(I,5))
2100 NEXT I
2110 REM ----- Add input pulses
2120 IF P0=0 THEN 2180
2130 FOR I=1 TO P0
2140 N1=J(P1(I),2)
2150 Z1=Z(INT(N1+1)/2)
2160 V2(N1,T0)=V2(N1,T0)+P(I,T)*Z1/(Z1+J(P1(I),4))
2170 NEXT I
2180 REM----- Store for plotting if necessary
2190 IF INT((T-T3)/T4+0.01)<=T5 THEN 2410
2200 T5=INT((T-T3)/T4+0.01)
2210 FOR I=1 TO W0
2220 IF W1(I,1)=0 THEN 2400
2230 A=V1(W1(I,1))
2240 B=V2(W1(I,1),T0)
2250 GO TO W1(I,2) OF 2260,2280,2300,2330,2330
2260 W(I,T5)=A+B
```

```
2270 GO TO 2390
2280 W(I,T5)=(A-B)/Z(INT((W1(I,1)+1)/2))
2290 GO TO 2390
2300 IF A-B=0 THEN 2390
2310 W(I,T5)=(A+B)/(A-B)*Z(INT((W1(I,1)+1)/2))
2320 GO TO 2390
2330 W(I,T5)=(A↑2-B↑2)/Z(INT((W1(I,1)+1)/2))
2340 IF W1(I,2)=4 THEN 2390
2350 IF T5=1 THEN 2380
2360 W(I,T5)=W(I,T5-1)+W(I,T5)*T2*T4
2370 GO TO 2390
2380 W(I,T5)=W(I,T5)*T2
2390 NEXT I
2400 V3=I
2410 REM ----- Change var impedances
2420 IF O0=0 THEN 2510
2430 FOR I=1 TO O0
2440 N1=O1(I)*2
2450 N2=N1-1
2460 O2=Z(O1(I))
2470 GOSUB I OF 3730,3830,3930,4030,4130,4230,4330,4430,4530
2480 O2=O2 MAX 1.0E-12
2490 Z(O1(I))=O2
2500 NEXT I
2510 REM ---- Change var resistances
2520 IF R0=0 THEN 2660
2530 I=0
2540 FOR I=1 TO R0
2550 N1=J(R1(I),2)
2560 N2=J(R1(I),3)
2570 IF J(R1(I),1)=4 THEN 2600
2580 V6=V1(N1)+V2(N1,T0)
2590 GO TO 2610
2600 V6=(V1(N1)-V2(N1,T0))*J(R1(I),4)/Z1
2610 I6=V6/J(R1(I),4)
2620 GOSUB I OF 4630,4730,4830,4930,5030,5130,5230,5330,5430
```

```
2630 R2=R2 MAX 1.0E-12
2640 J(R1(I),4)=R2
2650 NEXT I
2660 REM ----- Flip switches
2670 IF S0=0 THEN 2740
2680 FOR I=1 TO S0
2690 S2=S(I,1)
2700 S3=(T>S(I,3)/T2)*S(I,2)+(V1(S2)+V2(S2,T0)>S(I,3))*(1-S(I,2))
2710 M(S2,1)=M(S2,1)*(1-2*S3)
2720 S(I,3)=S(I,3)+1.0E+70*S3
2730 NEXT I
2740 REM ----- Recalculate M from J where needed
2750 IF J0=1 THEN 2800
2760 FOR I1=2 TO J0
2770 I=J1(I1)
2780 GOSUB 500
2790 NEXT I1
2800 T0=T0+1-L0*(T0+1>L0)
2810 NEXT T
2820 REM-------Convert lengths and times back to their original values
2830 T1=T1*T2
2840 T3=T3*T2
2850 L=L*T2
2860 REM-----Fill W7 with trace parameters for plotting
2870 T6=INT((T1-T3)/T4/T2+0.01)
2880 DELETE W2,W7
2890 DIM W2(T6),W7(W0,4)
2900 W7=0
2910 FOR I=1 TO W0
2920 FOR I1=1 TO T6
2930 W2(I1)=W(I,I1)
2940 NEXT I1
2950 IF W1(I,2)=3 THEN 2990
2960 CALL "MAX",W2,V3,L9
2970 CALL "MIN",W2,V4,L9
2980 GO TO 3010
```

```
2990 V3=Z5
3000 V4=0
3010 IF ABS(V3)>ABS(V4) THEN 3060
3020 W7(I,4)=1
3030 L9=-V3
3040 V3=-V4
3050 V4=L9
3060 N5=INT(LGT(V3))
3070 N6=10↑(LGT(V3)-INT(LGT(V3)))
3080 N7=1*(N6>5)+5*(N6>2)*(N6<=5)+2*(N6<=2)
3090 IF N7<>1 THEN 3110
3100 N5=N5+1
3110 W7(I,1)=N7
3120 W7(I,2)=N5
3130 W7(I,3)=V3
3140 NEXT I
3150 END
```

```
3160 REM----SINGLE PLOT ROUTINE
3170 FOR I=1 TO V0
3180 PAGE
3190 VIEWPORT 5,95,5,95
3200 N7=W7(I,1)
3210 N5=W7(I,2)
3220 V3=W7(I,3)
3230 N8=W7(I,4)
3240 WINDOW 0,T6,-0.2*N7*10↑N5,N7*10↑N5
3250 AXIS T6/10,N7*10↑(N5-1)
3260 FOR I1=1 TO T6
3270 W2(I1)=W(I,I1)*(1-2*N8)
3280 NEXT I1
3290 MOVE 0,0
3300 CALL "DISP",W2
3310 MOVE T1*0.15,-0.15*N7*10↑N5
3320 PRINT T4*T1/10;" /DIV   STARTING TIME = ";T3*T2;
3330 T$="VOLTAGE  CURRENT  IMPEDANCEPOWER    ENERGY   "
3340 S$=SEG(T$,W1(I,2)*9-8,9)
3350 IF W1(I,1)>0 THEN 3370
3360 S$=CHR(W1(I,2))
3370 MOVE T6,N7*10↑N5*0.8
3380 PRINT S$;" END ";W1(I,1);
3390 IF N8=0 THEN 3410
3400 PRINT "(INV)"
3410 MOVE T6,N7*10↑N5*0.8
3420 PRINT "J UNITS: ";N7;"E";N5-1;"/DIV";
3430 MOVE T6,N7*10↑N5*0.8
3440 PRINT USING "7A3E":"JJ MAX=";V3;
3450 COPY
3460 NEXT I
3470 END
```

```
3480 REM--TARGET LINE FOR APPEND UPDATE
3530 REM-----"SYSLIB/BERTHA/APPEND"
3580 REM-----This program segment is appended to the main
3630 REM-----program routine each time the program is run
3680 REM
3730 REM-----VAR IMPEDANCE ELT 1
3780 RETURN
3830 REM-----VAR IMPEDANCE ELT 2
3880 RETURN
3930 REM-----VAR IMPEDANCE ELT 3
3980 RETURN
4030 REM-----VAR IMPEDANCE ELT 4
4080 RETURN
4130 REM-----VAR IMPEDANCE ELT 5
4180 RETURN
4230 REM-----VAR IMPEDANCE ELT 6
4280 RETURN
4330 REM-----VAR IMPEDANCE ELT 7
4380 RETURN
4430 REM-----VAR IMPEDANCE ELT 8
4480 RETURN
4530 REM-----VAR IMPEDANCE ELT 9
4580 RETURN
4630 REM-----VARIABLE RESISTANCE 1
4680 RETURN
4730 REM-----VARIABLE RESISTANCE 2
4780 RETURN
4830 REM-----VARIABLE RESISTANCE 3
4880 RETURN
4930 REM-----VARIABLE RESISTANCE 4
4980 RETURN
5030 REM-----VARIABLE RESISTANCE 5
5080 RETURN
5130 REM-----VARIABLE RESISTANCE 6
5180 RETURN
```

```
5230 REM-----VARIABLE RESISTANCE 7
5280 RETURN
5330 REM-----VARIABLE RESISTANCE 8
5380 RETURN
5430 REM-----VARIABLE RESISTANCE 9
5480 RETURN
```

```
100 REM -----MULTI-TRACE GRAPHING ROUTINE (4054)
110 PAGE
120 PRINT "Do you wish to rescale any traces? (hit RET if no)"
130 PRINT "You have two options - to multiply a trace or scale to"
140 PRINT "another trace. First type in the trace you want to adjust,"
150 PRINT "then a comma. If you simply want to multiply a trace then"
160 PRINT "type in number. If you want to scale to another trace then"
170 PRINT "type in the other trace.  Enter changes one at a time,"
180 PRINT "hitting RET after each. To end just hit RET."
190 INPUT U$
200 IF U$="" THEN 390
210 Z$=U$
220 GOSUB 1040
230 U5=M9
240 REM - DETERMINE IF 2ND ENTRY A NUMERIC CONSTANT OR A TRACE
250 Z$=SEG(U$,POS(U$,",",1)+1,1)
260 V8=ASC(Z$)
270 Z$=SEG(U$,POS(U$,",",1)+1,LEN(U$)-POS(U$,",",1))
280 IF V8<65 THEN 350
290 REM 2ND ENTRY IS A TRACE - TRANSFER SCALING FACTORS
300 GOSUB 1040
310 V5=M9
320 W7(U5,1)=W7(V5,1)
330 W7(U5,2)=W7(V5,2)
340 GO TO 380
350 REM 2ND ENTRY IS A NUMERIC CONTANT - ADJUST SCALING FACTOR N6 IN W7
360 V9=VAL(Z$)
370 W7(U5,1)=W7(U5,1)/V9
380 GO TO 190
390 PRINT "JHOW MANY DIFFERENT GRAPHS DO YOU WANT?";
400 INPUT W9
410 DELETE W8
420 DIM W8(W9,6)
430 W8=0
440 FOR I9=1 TO W9
450 PRINT "JHOW MANY TRACES ON GRAPH ";I9;" ?(MAX=5) ";
460 INPUT J8
```

```
470 W8(I9,6)=J8
480 FOR I8=1 TO J8
490 PRINT "    Input trace #";I8;":";
500 INPUT Z$
510 GOSUB 1040
520 W8(I9,I8)=M9
530 NEXT I8
540 NEXT I9
550 REM - START PLOTTING ROUTINE
560 T1=(T1-T3)/T2
570 FOR I=1 TO W9
580 RESTORE 760
590 PAGE
600 FOR I2=1 TO W8(I,6)
610 IF W8(I,I2)=0 THEN 1000
620 FOR I1=1 TO T1
630 W2(I1)=W(W8(I,I2),I1)
640 NEXT I1
650 REM - RETRIEVE SCALING VALUES FROM MATRIX W7
660 N8=W7(W8(I,I2),4)
670 V3=W7(W8(I,I2),3)
680 N5=W7(W8(I,I2),2)
690 N6=W7(W8(I,I2),1)
700 VIEWPORT 0,87,5,95
710 WINDOW 0,T1,-0.1*N6*10↑N5,N6*10↑N5
720 IF I2>1 THEN 760
730 AXIS T1/10,N6*10↑(N5-1)
740 MOVE T1*0.15,-0.15*N6*10↑N5
750 PRINT T2*T1/10;" /DIV  STARTING TIME = ";T2*T3;
760 DATA 0,85,7,21,5
770 REM - DETERMINE DASH PATTERN
780 READ G9
790 DASH G9
800 MOVE 0,0
810 FOR I1=1 TO T1
820 W2(I1)=W2(I1)*(N8=0)-W2(I1)*(N8=1)
```

```
830 DRAW I1,W2(I1)
840 NEXT I1
850 T$="VOLTAGE  CURRENT  IMPEDANCEPOWER    ENERGY   "
860 S9=W1(W8(I,I2),2)*9-8
870 S$=SEG(T$,S9,9)
875 IF S9<38 THEN 880
876 S$=CHR(W1(W8(I,I2),2))
880 VIEWPORT 0,100,5,95
890 MOVE 0.9*T1,(1-(I2-1)*0.2)*N6*10↑N5
900 RDRAW 0.08*T1,0
910 PRINT "JJHHHHH";S$;" END ";W1(W8(I,I2),1);
920 IF N8=0 THEN 940
930 PRINT " (INV)HHHHHH";
940 MOVE 0.9*T1,(1-(I2-1)*0.2)*N6*10↑N5
950 PRINT "JJJUNITS: ";N6;"E";N5-1;"/DIV";
960 MOVE 0.9*T1,(1-(I2-1)*0.2)*N6*10↑N5
970 PRINT USING "8A3E":"JJJJMAX=";V3;
980 NEXT I2
990 COPY
1000 NEXT I
1010 T1=T1*T2+T3
1030 END
1040 REM - DETERMINE POSITION OF TRACE IN MATRIX W1 AND MATRIX W
1050 Z9=VAL(Z$)
1060 Z$=SEG(Z$,1,1)
1070 Z8=1+(Z$="I")+2*(Z$="Z")+3*(Z$="P")+4*(Z$="E")
1071 IF Z9>0 THEN 1080
1072 Z8=ASC(Z$)
1080 M9=0
1090 FOR I7=1 TO W0
1100 IF W1(I7,1)<>Z9 THEN 1140
1110 IF W1(I7,2)<>Z8 THEN 1140
1120 M9=I7
1130 GO TO 1150
1140 NEXT I7
1150 RETURN
```

```
1870 REM -------------------------PRINTOUT ROUTINE
1880 PAGE
1890 PRINT "BERTHA - NRL GAMBLE GROUP TRANSMISSION LINE CODE ";
1900 PRINT "  CONFIGURATION LISTING"
1910 CALL "TIME",I$
1920 PRINT "JCONFIG. NAME: ";B$;"        ";I$
1930 PRINT "JQUANTITY                              VARIABLE NAME";
1940 PRINT "                      VALUE"
1950 PRINT USING "18A18X1A20X4D":"Number of elements";"N";N
1960 PRINT USING "10A25X2A20X4D.3D":"Total time";"T1";T1
1970 PRINT USING "8A27X2A20X4D.3D":"Timestep";"T2";T2
1980 PRINT USING "19A16X2A20X4D.3D":"Waveform start time";"T3";T3
1990 PRINT USING "18A17X2A22X2D":"Waveform plot step";"T4";T4
2000 PRINT USING "15A20X2A20X4D":"Number of plots";"W0";W0
2010 PRINT USING "22A13X2A20X4D":"Number of input pulses";"P0";P0
2020 PRINT USING "24A11X2A20X4D":"Number of var impedances";"O0";O0
2030 PRINT USING "19A16X2A20X4D":"Number of var loads";"R0";R0
2040 PRINT USING "18A17X2A20X4D":"Number of switches";"S0";S0
2050 PRINT "JELEMENT NO         L                  Z             V0";
2060 PRINT "              I0"
2070 FOR I=1 TO N
2080 PRINT USING "2X3D8X2E5X2E3X2E4X2E":I;L(I);Z(I);V0(I);I0(I)
2090 NEXT I
2100 PRINT "JJUNC #    J(I,1) TYPE    J(I,2) QUANT     J(I,3) QUANT    ";
2110 PRINT "  J(I,4) QUANT"
2120 DELETE H$
2130 H$="ResistSimpleShnResSerResParTeeSerTeeComOpSComClSSBrClS"
2140 FOR I=1 TO N+1
2150 J$=SEG(H$,J(I,1)*6-5,6)
2160 PRINT USING "2X3D6X2D2X6A5X2D2X7AS":I;J(I,1);J$;J(I,2);"End Num"
2170 GO TO J(I,1) OF 2180,2210,2290,2290,2230,2230,2250,2250,2270
2180 PRINT USING "7X1DS":J(I,3);
2190 PRINT USING "2X7A2E1X7A":"-------";J(I,4);"Resist "
2200 GO TO 2330
2210 PRINT USING "6X2D2X7A7X1D2X7A":J(I,3);"End Num";J(I,4);"-------"
2220 GO TO 2330
2230 PRINT USING "6X2D2X7A6X2D2X7A":J(I,3);"End Num";J(I,4);"End Num"
```

```
2240 GO TO 2330
2250 PRINT USING "2E1X6A7X1D2X7A";J(I,3);"SwTime";J(I,4);"-------"
2260 GO TO 2330
2270 PRINT USING "1X2E1X5A7X1D2X7A";J(I,3);"BdVol";J(I,4);"-------"
2280 GO TO 2330
2290 PRINT USING "6X2D2x/A2E1XS";J(I,3);"End Num";J(I,4);
2300 J$=SEG("ShnResSerRes",(J(I,1)=4)*6+1,6)
2310 PRINT J$
2320 GO TO 2330
2330 NEXT I
2340 PRINT "JINPUT PULSE  END        VAR IMPEDANCE  ELT        ";
2350 PRINT "VAR RESISTANCE  END"
2360 FOR I=1 TO P0 MAX O0 MAX R0
2370 H$=SEG(P$,(I-1)*7+1,6)
2380 I$=SEG(O$,(I-1)*7+1,6)
2390 O$=SEG(R$,(I-1)*7+1,6)
2400 PRINT USING "2X6A4X3D13X6A4X3D13X6AS";H$;P1(I);I$;O1(I);O$;
2410 PRINT USING "5X3D";R1(I)
2420 NEXT I
2430 PRINT "JPLOT LISTING      END  NUMBER      TYPE"
2440 FOR I=1 TO W0
2450 GO TO W1(I,2) OF 2490,2510,2540,2560,2580
2460 Z$=CHR(W1(I,2))
2470 PRINT USING "9A1X2D10X2D9X3A1A";"Plot No.:";I;W1(I,1);"   ";Z$;
2480 GO TO 2590
2490 PRINT USING "9A1X2D10X2D9X7A";"Plot No.:";I;W1(I,1);"Voltage"
2500 GO TO 2590
2510 PRINT USING "9A1X2D10X2D9X7A";"Plot No.:";I;W1(I,1);"Current"
2520 GO TO 2590
2530 IMAGE9A1X2D10X2D9X19A4D
2540 PRINT USING 2530;"Plot No.:";I;W1(I,1);"Impedance--Max Val=";Z5
2550 GO TO 2590
2560 PRINT USING "9A1X2D10X2D9X5A";"Plot No.:";I;W1(I,1);"Power"
2570 GO TO 2590
2580 PRINT USING "9A1X2D10X2D9X6A";"Plot No.:";I;W1(I,1);"Energy"
2590 NEXT I
2600 END
```

```
2610 REM------- CONFIGURATION SAVE ROUTINE
2620 PAGE
2630 PRINT "Configuration Save RoutineJJJJJ"
2640 PRINT "Enter the configuration name:  ";
2650 INPUT B$
2660 OPEN "$D/CONFIGS/CLIST";1,"F",Z$
2670 READ #1:C1
2680 DELETE A$
2690 DIM A$(C1+8)
2700 READ #1:A$
2710 C$="0000000"
2720 C$=REP(B$,1,LEN(B$))
2730 IF POS(A$,C$,1)<>0 THEN 2820
2740 C$="$D/CONFIGS/"&C$
2750 CREATE C$;1000,0
2760 C$=SEG(C$,12,7)
2770 A$=A$&C$
2780 A$=A$&"-"
2790 C1=C1+8
2800 CALL "rewind",1
2810 WRITE #1:C1,A$
2820 C$="$D/CONFIGS/"&C$
2830 OPEN C$;2,"F",Z$
2840 WRITE #2:2,N,T1,T2,T3,T4,W0,Z5,P0,O0,R0,S0,J0,L,Z,V0,I0,J,J1
2850 WRITE #2:W1,P1,P$,O1,O$,R1,R$
2860 CLOSE
2870 PRINT "JJJJFinished configuration save"
2880 END
```

```
2890 REM--------CONFIGURATION DELETE ROUTINE
2900 PAGE
2910 PRINT "Configuration Delete RoutineJJJJJ"
2920 PRINT "Enter the name of the configuration to be deleted:  ";
2930 INPUT B$
2940 OPEN "$D/CONFIGS/CLIST";1,"F",Z$
2950 READ #1:C1
2960 DELETE A$
2970 DIM A$(C1)
2980 READ #1:A$
2990 C2=POS(A$,B$,1)
3000 IF C2=0 THEN 3050
3010 C1=C1-8
3020 A$=REP("",C2,8)
3030 CALL "rewind",1
3040 WRITE #1:C1,A$
3050 CLOSE
3060 C$="$D/CONFIGS/0000000"
3070 C$=REP(B$,12,LEN(B$))
3080 KILL C$
3090 PRINT "JJJJFinished configuration delete"
3100 END
```

# APPENDIX D - PROGRAM SEGMENTS

The following program segments will correctly adjust the traveling wave voltages as the element impedance is changed. The first is a general program for any element, the second is a simplified version for an element of single timestep length and the third is a simplification for a purely capacitive element (Again, no correction is needed for a purely inductive element).

```
100 REM-----VOLTAGE CORRECTION FOR A CHANGING IMPEDANCE ELEMENT
110 REM-----CORRECTION FOR A MULTI-TIMESTEP ELEMENT
120 REM-----OF ARBITRARY IMPEDANCE
130 O2=O2 MAX 1.ØE-12
140 O4=O2/Z(O1(I))
150 FOR I1=Ø TO INT((L(I)+1.Ø5)/2)-1
160 I2=TØ-I1+LØ*(TØ<=I1)
170 I3=TØ-(L(I)-1-I1)+LØ*(TØ+I1+1<=L(I))
180 O3=V2(N1,I1)
190 V2(N1,I1)=(V2(N1,I1)*(O4+1)+V2(N2,I2)*(O4-1))/2
200 V2(N2,I2)=(V2(N2,I2)*(O4+1)+O3*(O4-1))/2
210 IF I1=I2 THEN 25Ø
220 O3=V2(N2,I1)
230 V2(N2,I1)=(V2(N2,I1)*(O4+1)+V2(N1,I2)*(O4-1))/2
240 V2(N1,I2)=(V2(N1,I2)*(O4+1)+O3*(O4-1))/2
250 NEXT I1
260 REM-----END OF PROGRAM SE. ENT
```

```
100 REM-----VOLTAGE CORRECTION FOR A CHANGING IMPEDANCE ELEMENT
110 REM-----CORRECTION FOR A SINGLE TIMESTEP ELEMENT
120 REM-----OF ARBITRARY IMPEDANCE
130 O2=O2 MAX 1.ØE-12
140 O4=O2/Z(O1(I))
150 O3=V2(N1,TØ)
160 V2(N1,TØ)=(V2(N1,TØ)*(O4+1)+V2(N2,TØ)*(O4-1))/2
170 V2(N2,TØ)=(V2(N2,TØ)*(O4+1)+O3*(O4-1))/2
180 REM-----END OF PROGRAM SEGMENT
```

```
100 REM-----VOLTAGE CORRECTION FOR A CHANGING IMPEDANCE ELEMENT
110 REM-----CORRECTION FOR A CAPACITIVE (LOW Z) ELEMENT
120 O2=O2 MAX 1.ØE-12
130 O4=O2/Z(O1(I))
140 FOR I1=1 TO LØ
150 V2(N1,I1)=V2(N1,I1)*O4
160 V2(N2,I1)=V2(N2,I1)*O4
170 NEXT I1
180 REM-----END OF PROGRAM SEGMENT
```

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